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IN-FLIGHT SIMULATION OF MINIMUM LONGITUDINAL STABILITY FOR LARGE DELTA-WING TRANSPORTS IN LANDING APPROACH AND TOUCHDOWN

VOL. 1

TECHNICAL RESULTS

CALSPAN CORP.

PREPARED FOR

AIR FORCE FLIGHT DYNAMICS LABORATORY

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IN-FLIGHT SIMULATION OF MINIMUM LONGITUDINAL STABILITY FOR LARGE DELTA-WING TRANSPORTS IN LANDING APPROACH AND TOUCHDOWN

VOLUME I TECHNICAL RESULTS

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16. Abstract

An in-flight simulation to investigate minimum longitudinal stability for large delta-wing transports in landing approach and touchdown (including ground effect) was conducted using the USAF/Calspan Total In-Flight Simulator (TIFS) airplane. Aerodynamic, inertial and control data for this class of airplane were obtained from a prototype Concorde package supplied by the FAA. The simulation program involved the examination of 20 configurations by four evaluation pilots. The configurations evaluated were based upon a systematic variation of the longitudinal stability characteristics for this class of airplane. These variations were designed to examine the influence of pitch stiffness, backsideness, pitch damping and nonlinear pitching moment effects on pilot acceptability of minimum longitudinal stability for the landing approach task. A total of 61 evaluations was performed. In general, the most demanding task appeared to be longitudinal control in flare and touchdown due to the sluggish nature of the attitude response and the strong nose-down pitching motion introduced by the simulated ground effect. The results indicate that the level of turbulence encountered in the approach will significantly affect the minimum longitudinal stability acceptable for the task. Specifically, the minimum acceptable boundary (based on a Cooper-Harper pilot rating of 6.5) determined in this investigation occurred at a value of time to double amplitude (computed from the unstable aperiodic root of the longitudinal characteristic equation (T_2)) equal to 2.5 seconds in light turbulence and at 4.25 seconds in moderate turbulence. These results could be significantly influenced by ground effect characteristics, pitch control sensitivity, pilot training, restricted visibility and night landings.

This report, Volume I of two parts is being published by the FAA Systems Research and Development Service to help expedite distribution and availability to those interested in the results. As indicated in the FOREWORD, the Volume II may be obtained from the Air Force Flight Dynamics Laboratory (FGF), Wright-Patterson Air Force Base, Ohio 45433.

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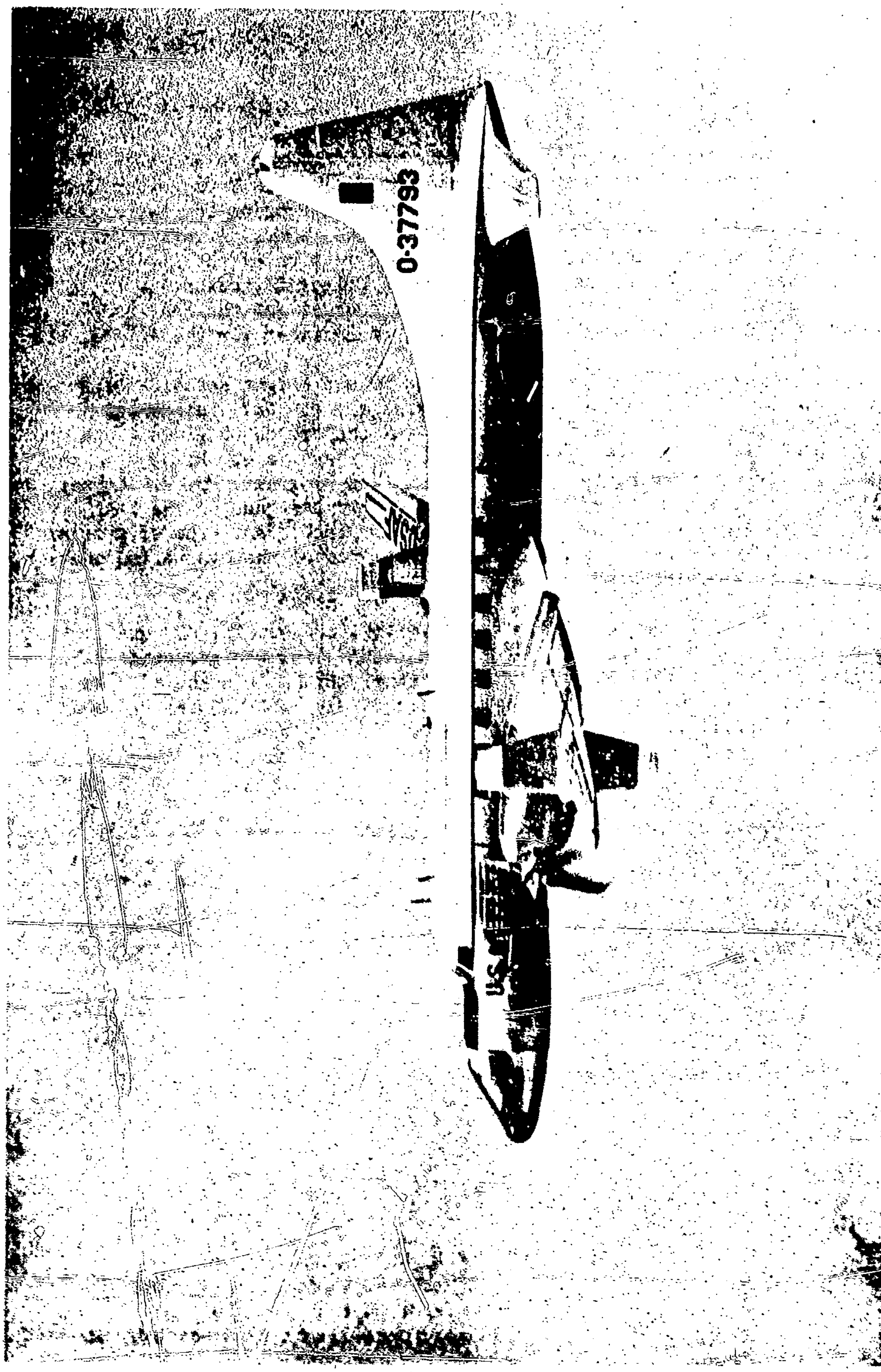

TOTAL IN-FLIGHT SIMULATOR (TIFS)

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FOREWORD

This final technical report was prepared by Calspan Corporation (formerly Cornell Aeronautical Laboratory, Inc.), Buffalo, New York, under Contract F33615-72-C-1386, Project No. 920K, "Flight Research Program for Large Aircraft." The work was performed under the sponsorship of the Federal Aviation Administration (FAA), and was administrated under the direction of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Mr. Jerome Teplitz (RD-741) was Project Manager for the FAA, and Mr. James R. Pruner (AFFDL/FGC) was the Project Engineer for the Air Force.

The work reported herein was performed by the Flight Research Department of Calspan. Dr. P.A. Reynolds was Program Manager, Mr. G.J. Fabian was Assistant Program Manager, Mr. R. Wasserman was the Project Engineer, and Mr. J.F. Mitchell served as Assistant Project Engineer and Safety Pilot. Acknowledgement is given to the evaluation pilots on this program: Mr. R.P.Harper, Jr. of Calspan, Lt/Col. T.D. Benefield, USAF (currently assigned to the FAA), Mr. F.J. Drinkwater, III of NASA/AMES, and Mr. D. Tuck, FAA. The efforts of Mr. R. Abrams (FAA), who assisted in the performance of the evaluation phase of the program, are also appreciated.

The successful completion of this investigation was largely due to the excellent performance of the TIFS flight and ground crew who are especially acknowledged here. Safety Pilots: Nello Infanti, Franklin Eckhart, Edward Boothe; Electronic Engineers: Arno Schelhorn, James Dittenhauser, Ronald Huber; Electronic Technicians: David Begier, Fred Juliano; Crew Chiefs: Raymond Miller and David Kostrubanic; Computer Programming: Clarence Mesiah.

This report was submitted by the authors in December 1972. It is being published simultaneously as Calspan Report No. AK-5084-F-1. The report is in two volumes: Volume I contains the technical results of the experiment, and Volume II presents specific background information on the experiment and the complete pilot comments. Volume II may be obtained on request from Air Force Flight Dynamics Laboratory (FGF), Wright-Patterson Air Force Base, Ohio 45433.

This technical report has been reviewed and approved.

C.B. WESTBROOK
Chief, Control Criteria Branch
Flight Control Division
Air Force Flight Dynamics Laboratory

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont.)

LIST OF ILLUSTRATIONS (cont.)

LIST OF TABLES

LIST OF SYMBOLS

b = Reference span of wing, feet

$(BW)_{MIN}$ = Value of the closed-loop bandwidth which the pilot is trying to achieve in precision tracking tasks, rad/sec

$\bar{c}$ = Mean aerodynamic chord, feet

C_D = Drag coefficient = $D/\bar{q}S$

C_{D_α} = $\partial C_D/\partial\alpha$, rad^{-1}

$C_{D_{\delta_e}}$ = $\partial C_D/\partial\delta_e$

C_L = Lift coefficient = $L/\bar{q}S$

C_{L_o} = Lift coefficient at zero angle of attack

C_{L_α} = $\partial C_L/\partial\alpha$, rad^{-1}

$C_{L_{\dot\alpha}}$ = $\partial C_L/\partial\left(\frac{\dot\alpha\ell}{V}\right)$, rad^{-1}

$C_{L_{\delta_e}}$ = $\partial C_L/\partial\delta_e$, rad^{-1}

C_{L_q} = $\partial C_L/\partial\left(\frac{q\ell}{V}\right)$, rad^{-1}

C_ℓ = $L/\bar{q}\ell S$

C_m = Pitching moment coefficient = $M/\bar{q}\ell S$

C_{m_o} = Pitching moment coefficient at zero angle of attack

$C_{m_{1,2,3}}$ = Coefficients of power series expansion of C_m as a function of α

C_{m_α} = $\partial C_m/\partial\alpha$, rad^{-1}

$C_{m_{\dot\alpha}}$ = $\partial C_m/\partial\left(\frac{\dot\alpha\ell}{V}\right)$, rad^{-1}

C_{m_q} = $\partial C_m/\partial\left(\frac{q\ell}{V}\right)$, rad^{-1}

C_{m_V} = $\partial C_m/\partial V$, (ft/sec)$^{-1}$

C_n = $N/\bar{q}\ell S$

C_{n_β} = $\partial C_n/\partial\beta$, rad^{-1}

$C_{n_{\delta_a}}$ = $\partial C_n / \partial \delta_a$, rad^{-1}

C_x = $-C_D \approx -D/\bar{q}S$

d = Height of mean aerodynamic chord/semi-span

D = Drag, positive along negative x wind axis, lb

dB = Decibel units for Bode amplitude, where amplitude in dB = $20 \log_{10}$ (amplitude)

E = Constant term of longitudinal characteristic equation

$F(d)$ = Normalized lift ground effect function

$F_1(d)$ = Normalized pitching moment ground effect function

F_{AW} = Aileron wheel force, lb

F_{ES} = Elevator wheel force, positive aft, lb

F_{RP} = Rudder pedal force, lb

F_S = Elevator stick force, positive aft, lb

$F_{x_B}, F_{y_B}, F_{z_B}$ = Component of aerodynamic and thrust forces along the x , y , z body axes, respectively, lb

g = Gravitational constant, 32.17 ft/sec^2

h = Absolute altitude of airplane c.g., feet

h_{p_c} = Commanded change in airplane altitude at the pilot station, feet

h_p/δ_e = Open-loop altitude transfer function of airplane at pilot station, ft/deg or ft/rad

h_{p_e} = $(h_{p_c} - h_p)$, Error between the commanded altitude and the airplane altitude at the pilot station, feet

i_M = $(\alpha_M - \alpha_{air})$, Incidence angle between body axis of the model and that axis system parallel to the TIFS body axis, degrees

i_T = Incidence angle of engine thrust line with respect to body axis in the x-z plane (positive for thrust vector pointed upwards), deg

I_{xx}, I_{yy}, I_{zz} = Moments of inertia about the x , y , z body axes, respectively, slug-ft^{-2}

LIST OF SYMBOLS (cont.)

I_{xz}	=	Product of inertia about the x, z body axes, slug-ft^{-2}
K_D	=	Induced drag coefficient
K_p	=	Steady-state pilot gain, lb/deg or lb/rad
(K_1+K_2s)	=	Forward loop lead compensator for altitude closure
ℓ	=	Reference length of simulated airplane, feet
L	=	Lift, positive along negative z wind axis, lb
ℓ_x	=	Distance along the fuselage reference line between the c.g. and the pilot's station, positive for c.g. aft of the pilot station, feet
L,M,N	=	Moment vector components about the x, y, z body axis, respectively, ft-lb
M_α	=	$\frac{1}{I_{yy}}\frac{\partial M}{\partial \alpha}$, rad/sec^2/rad
m	=	Mass of airplane, slugs
n	=	Normal load factor, g units
n_y, n_z	=	Lateral, normal acceleration respectively, g units
p,q,r	=	Roll, pitch, and yaw rates, respectively, deg/sec
p_I,q_I,r_I	=	Inertial angular velocity components about the x, y, z body axes, respectively, degrees/second
$\bar{q}$	=	Dynamic pressure = $\frac{1}{2}\rho V^2$, lb/ft^2
s	=	Laplace operator, sec^{-1}
S	=	Reference area of wing, (feet)^2
T_m	=	Total model thrust, lb
T_2	=	Time to double amplitude computed from the unstable aperiodic root of the linearized longitudinal characteristic equation, seconds

LIST OF SYMBOLS (cont.)

$T_{1/2_{SP}}$	=	Time to half amplitude calculated from short period approximation of attitude, seconds
$T_{2_{SP}}$	=	Time to double amplitude calculated from short period approximation of attitude, seconds
T_{2_α}	=	Time to double amplitude measured from angle of attack response to elevator, seconds
$T_{1/2_\theta}$	=	Time to half amplitude of equivalent short term attitude response to elevator, seconds
T_{2_θ}	=	Time to double amplitude of equivalent short term attitude response to elevator, seconds
u_I, v_I, w_I	=	Inertial velocity components along the x, y, z body axes, respectively, feet/second
V	=	True airspeed of the airplane center of gravity, ft/sec
V_I	=	Inertial airspeed of the airplane in earth surface axes, feet/second
W	=	Airplane weight, lb
x, y, z	=	Body axes, x-z plane is in the plane of symmetry of the airplane with x directed forward parallel to the fuselage reference line, z directed downward, and y directed out the right wing
Y	=	Touchdown distance from runway threshold, feet
Y_w	=	Side force, positive along positive y wind axis, lb
z_T	=	Thrust pitching moment arm component (positive along + z body axis measured relative to the c.g.), ft
$\dot{(\ )}$	=	First derivative with respect to time, sec^{-1}
$\ddot{(\ )}$	=	Second derivative with respect to time
α	=	Total angle of attack with respect to true airspeed, rad or deg
α_I	=	Inertial angle of attack referenced to inertial velocity vector, degrees
α/δ_e	=	Open-loop angle-of-attack transfer function of the airplane

LIST OF SYMBOLS (cont.)

β	=	Total angle of sideslip with respect to true airspeed rad or deg
β_I	=	Inertial angle of sideslip referenced to inertial velocity vector, degrees
γ	=	Flight path angle, deg
$d\gamma/dV$	=	Flight path stability parameter, deg/knot
δ_a	=	Equivalent aileron surface deflection, positive right T.E. down, deg or rad
δ_e	=	Equivalent elevator surface deflection, positive T.E. down, deg or rad
δ_e/F_s	=	Open-loop transfer function of elevator surface to elevator stick force, deg/lb or rad/lb
δ_r	=	Equivalent rudder surface deflection, positive T.E. left, deg or rad
δ_x	=	Throttle lever position, deg
$[\Delta A/\Delta \phi]_\theta$	=	Slope of Bode amplitude with phase for the airplane plus pilot time delay at reference frequency, dB/deg
ζ_{FS}	=	Damping ratio of feel system
ζ_{SP}	=	Damping ratio of the longitudinal short period mode
θ	=	Pitch angle, deg or rad
ϕ_θ	=	Phase angle of the airplane plus pilot time delay at the reference frequency, deg
θ_c	=	Commanded change in airplane pitch attitude, deg or rad
θ_e	=	$(\theta_c - \theta)$, Error between the commanded pitch attitude and the airplane pitch attitude, deg or rad
θ/δ_e	=	Open-loop pitch transfer function of airplane
θ/θ_e	=	Open-loop pitch transfer function of airplane plus control system plus pilot
λ	=	Aperiodic root magnitude, sec^{-1}

LIST OF SYMBOLS (cont.)

ρ	=	Air density, slugs/ft^3
σ	=	Mean square gust intensity
$\sigma_{V_{g_{MAX}}}$	=	Maximum value of total velocity mean square gust intensity, ft/sec
τ_{p_1}	=	Time constant of pilot's lead element, sec
τ_{p_2}	=	Time constant of pilot's lag element, sec
ϕ	=	Bank angle, deg or rad
ψ	=	Yaw angle, deg or rad
ω_θ	=	Reference frequency, rad/sec
$\omega_{n_{FS}}$	=	Undamped natural frequency of feel system, rad/sec
$\omega_{n_{SP}}$	=	Undamped natural frequency of the longitudinal short period mode, rad/sec

SUBSCRIPTS

A	=	Aerodynamic
B	=	Body axis
CW	=	Crosswind
g	=	Gust
GE	=	Ground effect
I	=	Inertial
IGE	=	In ground effect
M	=	Model body axis
MT	=	Axis system in the model parallel to the TIFS body axis
NT	=	Nonequilibrium
O	=	Initial condition
OGE	=	Out of ground effect
p	=	Pilot's location
S	=	Stability axis
t	=	Trim
T	=	Thrust
TCG	=	At the TIFS center of gravity

SECTION I

INTRODUCTION

This report presents the results of an in-flight simulation program to generate data on the minimum acceptable longitudinal stability of large delta-wing transports in the landing approach flight phase.

The objective of this program was to generate data for use in establishing flight characteristics criteria for airworthiness certification and issuance of operational limitations for supersonic transports during landing approach. The evaluation program was specifically directed toward definition of a minimum acceptable level of longitudinal stability of the unaugmented delta-wing transport airplane. This was accomplished by a systematic variation of static longitudinal stability of the airplane. In addition, the effects of: (1) curvature of the pitching moment vs. angle-of-attack curve, (2) increased pitch damping, and (3) backsidedness (variation of induced drag) on airplane acceptability were also examined to determine their influence on a minimum level of static stability. The basic data package used for this program was supplied by the FAA and consisted of aerodynamic data and control system characteristics of an unaugmented prototype Concorde airplane. This data defined a reference airplane configuration from which the above parameter variations were made.

For this experiment the in-flight simulator used was the TIFS airplane. The TIFS airplane is a research tool which permits a duplication of the motion of the simulated airplane pilot station, and the instrument and visual cues experienced in the actual performance of the landing approach task to a simulated touchdown. This permitted the evaluation pilot to assess the complete approach problem including localizer acquisition, glide slope acquisition under instrument conditions and control of flare and touchdown (with ground effect) under visual conditions. Glide slope errors, localizer offset error, crosswind and turbulence were introduced electronically into the evaluation task to allow the evaluation pilot to examine the simulated aircraft under various operational requirements.

The report is divided into two volumes. Each volume is subdivided into various sections. Volume I is essentially a summary of the experiment, while Volume II documents the experiment and the analysis of data in greater detail and provides specific background information for the contents of Volume I. The following is presented in the sections of Volume I:

Section II - Technical Discussion which describes the parameters varied as well as the effects of these variations on classical stability and control parameters.

Section III - Describes the experiment, the TIFS airplane and the evaluation aids provided the pilot.

Section IV - Pilot comment synopses and discussion of the experimental results.

Section V - Contains a summary of the experimental results and conclusions based on the data obtained in this investigation.

SECTION II

TECHNICAL DISCUSSION

2.1 PURPOSE OF THE EXPERIMENT

The in-flight evaluation program was designed to specifically examine the effect of static longitudinal instability on landing approach handling characteristics of large delta-wing transports. The objective of the program was the determination of a minimum acceptable level of static instability for the bare unaugmented airframe. The experiment was performed using the Total In-Flight Simulator (TIFS) airplane on which were programmed the equations of motion and the aerodynamic and control system characteristics which describe a large delta-wing jet transport during the landing approach flight phase. Included in the description of the aerodynamics of the airplane configurations investigated were the effects of proximity to the ground. Application of the TIFS airplane to this experiment allowed all cues (motion, instrument, and visual) to be accurately presented to the evaluation pilot. This was accomplished by flying the task through the critical flare and simulated touchdown under actual operational conditions. Previous in-flight and ground simulation experiments in this area have not been performed on equipment that could combine all of these factors, with the same realism.

2.2 DESCRIPTION OF THE CONFIGURATIONS EVALUATED

The design of the handling qualities experiment for this program began with definition of the aerodynamic stability derivatives for the particular type of airplane configuration under investigation. A complete description of the aerodynamic stability and control derivatives is presented in Volume II of this report. These derivatives were then modified to specifically examine the effects of static longitudinal instability on the landing task. Specifically, a baseline configuration was determined from an FAA supplied data package of an unaugmented prototype Concorde airplane. The program conducted consisted of performing variations in the following parameters:

a) Static instability for a linear pitching moment curve by modification of C_{m_α} to achieve the following selected times to double amplitude (T_2) based on the aperiodic unstable root of a linearized longitudinal characteristic equation: T_2 = 60 seconds, 8 seconds, 4 seconds and 2 seconds. In addition, a stable configuration was introduced to serve as a reference point.

b) Changes in the parameters of the aerodynamic pitching moment coefficients to investigate nonlinear C_{m_α} effects.

c) Changes in the shape of the drag polar to examine the effects of backside operation vs. operation in the bucket of the trim drag curve with velocity for statically unstable airplanes.

d) Changes in (C_{m_q} + $C_{m_{\dot{\alpha}}}$) to evaluate the effect of pitch damping.

When variation d) was used, the static stability (C_{m_α}) was also varied such that the specific values of T_2 under investigation were still maintained at the preselected values. Using these variations, a matrix of airplane configurations was established from which twenty configurations were selected for the in-flight investigation. The matrix of configurations is presented in Table I based on the definitions in the following chart.

Derivative	Identification	Description
$C_{m_q} + C_{m_{\dot{\alpha}}}$	I	Baseline value @ 53% c.g.
	II	5 times the baseline value
$C_m(\alpha)$	0	Linear $(\partial C_{m_\alpha}/\partial\alpha = 0)$
	1	Baseline nonlinearity $(\partial C_{m_\alpha}/\partial\alpha = .0002\ \text{deg}^{-2})$
	2	Nonlinearity twice baseline value $(\partial C_{m_\alpha}/\partial\alpha = .0004\ \text{deg}^{-2})$
$d\gamma/dV$	K_b	Baseline drag polar (backside operation)
	K_0	Drag polar to place airplane in bucket of power required curve at approach speed
Static Stability	A	Stable configuration/separated short period and phugoid modes
	B	60 second aperiodic divergence
	C	8 second aperiodic divergence
	D	4 second aperiodic divergence
	E	2 second aperiodic divergence

NOTE: Aperiodic divergence is based upon the unstable real root in the longitudinal characteristic equation.

For the experiment, the lateral-directional stability and control derivatives were not varied from the simplified baseline airplane values. The stability and control derivatives for the twenty evaluation configurations are tabulated in Appendix I of this volume.

Figure 1 illustrates the effects of the changes in the longitudinal derivatives on the time to double amplitude, determined from a linearized longitudinal characteristic equation root location, out of ground effect. For this situation the configurations with nonlinear C_{m_α} curves would be identical to those with the linear C_{m_α}, since all configurations were selected to essentially trim at the same condition out of ground effect.

TABLE I MATRIX OF EVALUATION CONFIGURATIONS

$C_{m_q}+C_{m_{\dot\alpha}}$	Baseline						5 x Baseline					
$\frac{\partial\gamma}{\partial V}$	Baseline (Backside)			Zero			Baseline (Backside)			Zero		
$C_m(\alpha)$ / C_{m_α}	linear	base-line non-linear	2 x non-linear	linear	base-line non-linear	2 x non-linear	linear	base-line non-linear	2 x non-linear	linear	base-line non-linear	2 x non-linear
Stable	1						13			20		
$T_2 \approx 60$ sec	2											
$T_2 \approx 8$ sec	3	6	8	10			14		17			
$T_2 \approx 4$ sec	4	7	9	11			15		18			
$T_2 \approx 2$ sec	5			12			16		19			

2.3 TIME TO DOUBLE AMPLITUDE

As discussed in Reference 1 and Appendix II of this report, the general criterion for a statically unstable airplane is the sign of the constant term in the characteristic equation. A measure of static instability is the

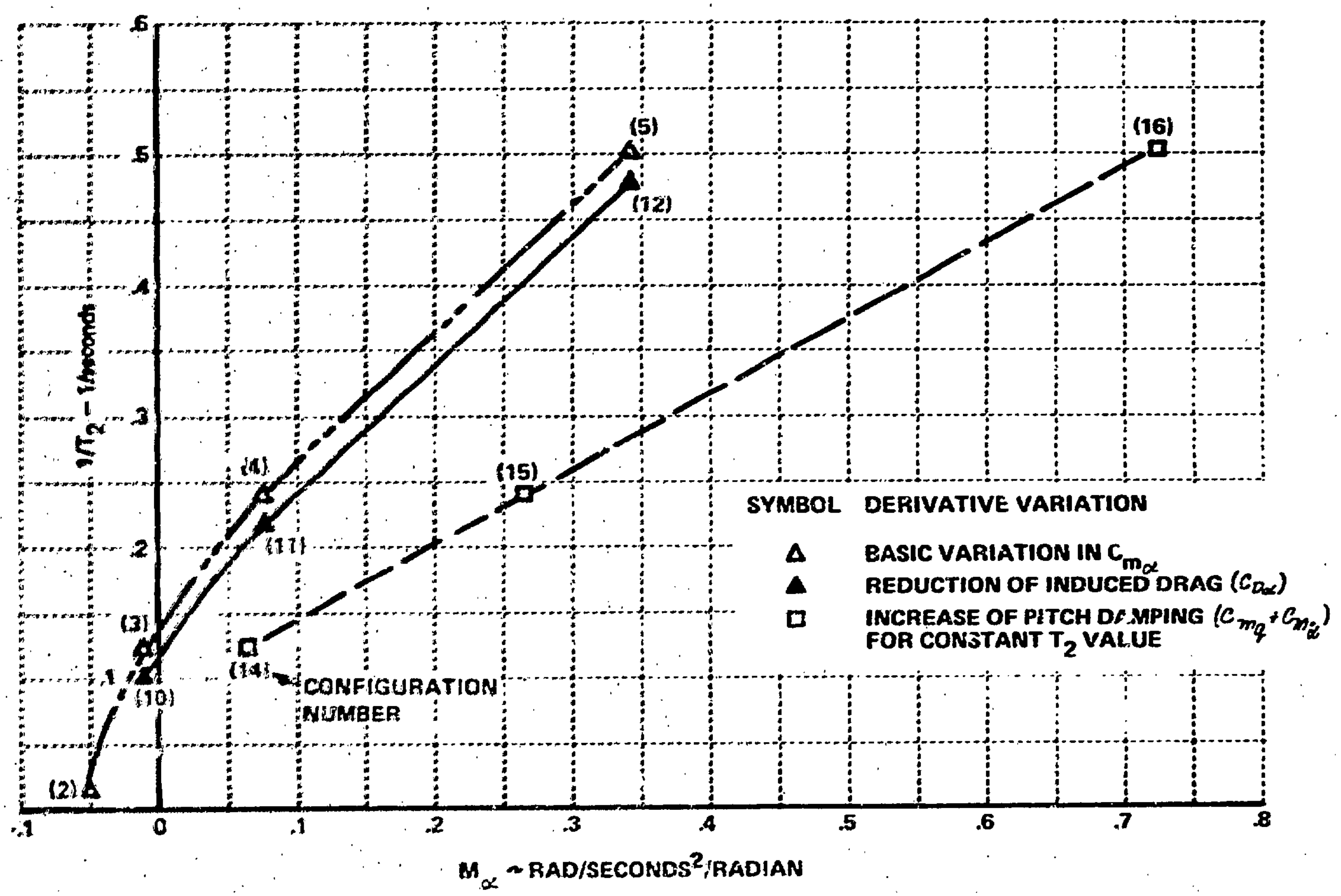


Figure 1 EFFECTS OF VARIATIONS IN C_{m_α}, C_{D_α}, AND (C_{m_q} & $C_{m_{\dot\alpha}}$) ON TIME TO DOUBLE AMPLITUDE (T_2) (OUT OF GROUND EFFECT)

divergence rate of the aperiodically unstable mode (time to double amplitude $\equiv T_2$ seconds). From a practical point, difficulties exist in attempting to measure this parameter for configurations with a relatively long time to double amplitude. Analysis presented in Appendix II of this report indicates that angle of attack response to elevator commands is a reasonable measure of T_2, especially for airplanes with relatively fast divergence rates. Figure 2 indicates the relationship exhibited by the configurations evaluated in this program between the T_2 determined from the unstable root of the longitudinal characteristic equation and the time to double amplitude measured from the angle of attack response to an elevator surface step (T_{2_α}) (see page 84 for measurement rules). For the configurations with linear C_{m_α} ($\partial C_m / \partial\alpha = 0$), for either nose-up or nose-down elevator inputs, the value of T_{2_α} is in reasonable agreement with the value of T_2 obtained from linearized theory, provided T_2 is less than ten seconds ($1/T_2 > .1$).

For the configurations with nonlinear C_{m_α} (C_{m_α} is a function of α) there exists very little correlation between measured divergence rate and that predicted by a linearized theory. When the elevator surface is moved trailing edge up, the measured T_{2_α} is significantly less than the value obtained from the linearized equations. The opposite is true for a trailing edge down elevator surface command. This is a result of the form of the C_{m_α} nonlinearity investigated in this program. An increase in angle of attack decreases static stability for the nonlinear configurations, while decreasing α increases static stability. Thus the data indicate that care must be exercized if T_{2_α} is used as a handling qualities parameter.

2.4 SHORT TERM ATTITUDE RESPONSE

In Appendix II of this report it is demonstrated that, for the configurations evaluated in this program, the short term attitude response to an impulse elevator command can be characterized by an "equivalent" first order time constant. The "equivalent" time can be reasonably determined from the smaller of the two roots calculated from the constant speed short period approximation. In addition, it is also shown in Appendix II that the slope of trim elevator position with "g" in constant altitude steady banked turns, at levels of incremental "g's" $\leq .2$, is indicative of whether the short term attitude response to elevator is stable or unstable*. This then presents the possibility of describing the statically unstable airplane configurations that were evaluated in this program in terms of short period parameters. Figure 3 indicates the correlation between the "equivalent" first order mode measured from attitude response to a nose-up elevator command and the "equivalent" mode predicted by the short period approximation. Figure 4 indicates the relationship between the "equivalent" pitch attitude first order mode and the time to double

* This parameter is related but not directly proportional to the classical stick-fixed maneuver margin.

FLAGGED SYMBOLS INDICATE NONLINEARITY IN C_{m_α} TWICE BASELINE VALUE

OPEN SYMBOLS INDICATE ELEVATOR TRAILING EDGE-UP INPUT

CLOSED SYMBOLS INDICATE ELEVATOR TRAILING EDGE-DOWN INPUT

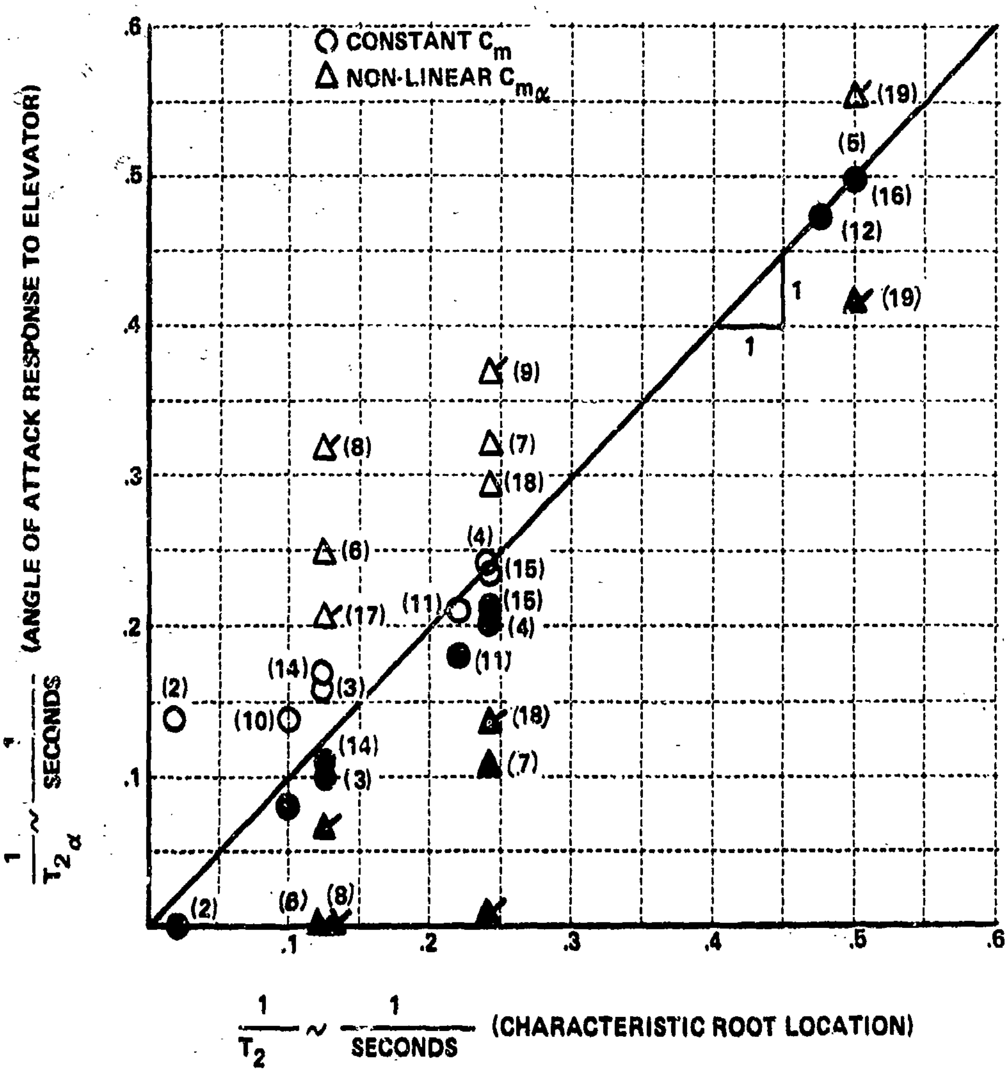


Figure 2 TIME TO DOUBLE AMPLITUDE (ANGLE OF ATTACK TIME HISTORY COMPARED TO CHARACTERISTIC ROOT LOCATION)

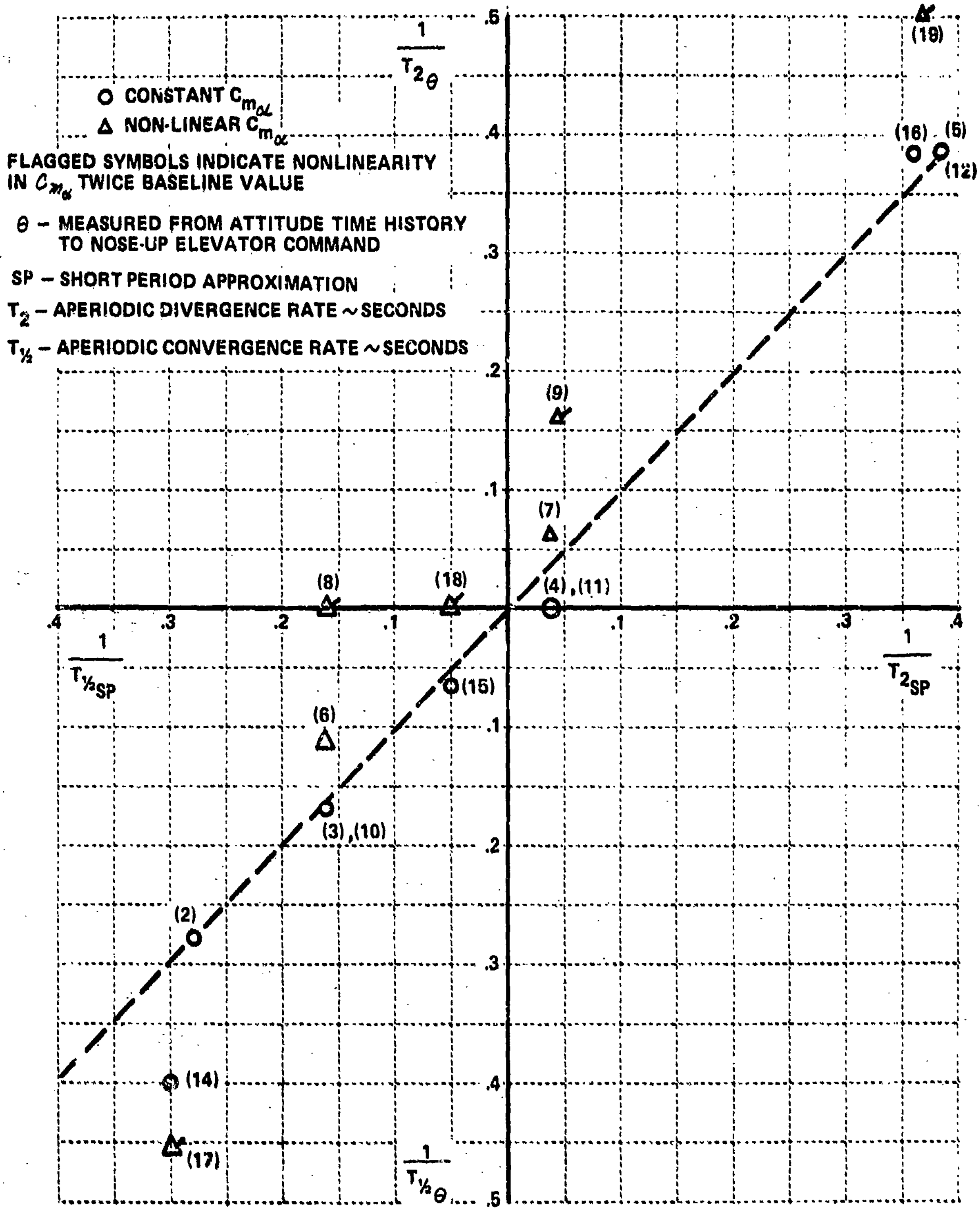


Figure 3 EQUIVALENT PITCH ATTITUDE TIME CONSTANT

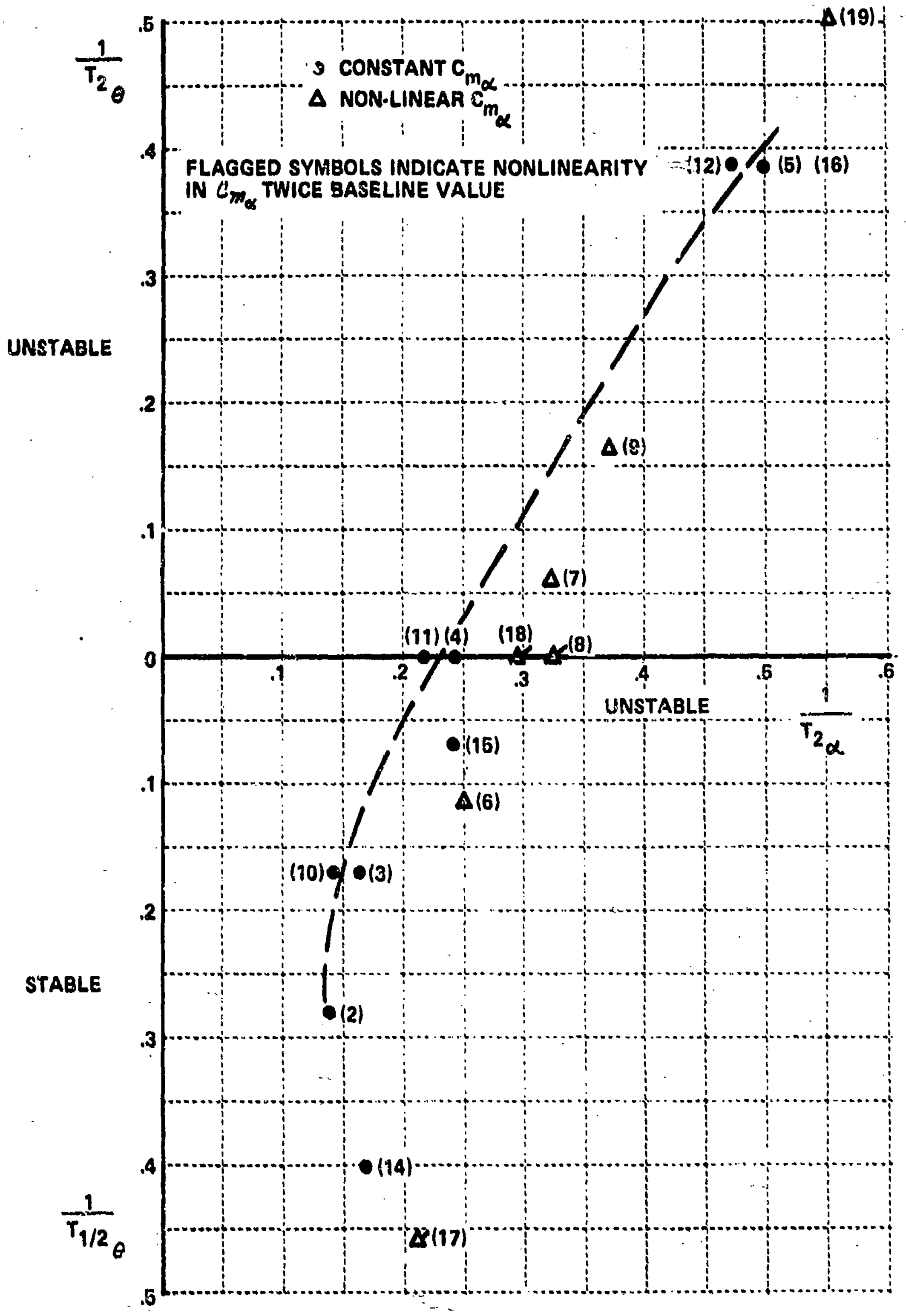


Figure 4 COMPARISON OF SHORT TERM ATTITUDE STABILITY WITH ANGLE OF ATTACK STABILITY

amplitude of angle of attack measured from responses to nose-up elevator control input. This figure indicates that the configurations evaluated in this research program can be separated into several regions based on the level of stability of either angle of attack or attitude response to an elevator command. The most obvious separation is into those configurations with stable short term attitude response in comparison with those configurations with an aperiodically unstable short term attitude response; for all configurations, angle of attack response exhibits an unstable divergence. This separation in the stability of the short term attitude response to elevator inputs might be of more importance to the pilot in controlling the airplane than the angle of attack divergence.

Based on the correlation between the "equivalent" first order mode in the pitch attitude response to elevator input and the short period approximation, it is then possible to present the configurations on a plane defined by the short period parameters (e.g., $\omega_{n_{sp}}^2$ and $2\zeta_{sp}\omega_{n_{sp}}$). Figure 5 illustrates the location of the configurations evaluated in this program. In essence the experiment can be interpreted as a variation in the short period frequency for two short period damping levels (at least for short term pitch attitude response). The location of the configurations shown on Figure 5 is based on the short period approximation including ground effect. For the form of ground effect used in this investigation (Section III, Volume II) the short period mode would increase frequency and damping as the airplane descends the glide path, thus in terms of these modal parameters, each configuration is actually a region in the short period plane. For clarity, only selected configurations are indicated, since the location of the nonlinear C_{m_α} configurations, and the configurations with reduced C_{D_α} would be essentially the same as for the basic configurations. Also shown on the figure are curves for 6 second and 3 second time to double amplitude computed when the short period approximation contains an unstable aperiodic root. From the trajectory of the short period modal parameters with altitude, it is obvious that the ground effect can have a significant influence when the airplane c.g. is less than 50 feet above the runway. At any altitude above 50 feet there is little influence of ground effect. As indicated in Section V of Volume II of this report the most significant feature of the ground effect would be the trim adjustments required by the pilot to compensate for the ground effect during the flare and touchdown maneuver to maintain a reasonable pitch attitude for landing.

The preceding discussion presented the poles (roots of the characteristic equations) obtained from a constant speed short-period approximation. The poles of the complete three-degree-of-freedom linearized longitudinal characteristic equation are presented in Appendix I of this report. Table II presents a comparison of the roots of the short period approximation $(-\lambda_1, -\lambda_2)$ with those obtained from the full characteristic equation $(1/T_{sp_1}, 1/T_{sp_2})$, for the configurations with real characteristic roots (out of ground effect).

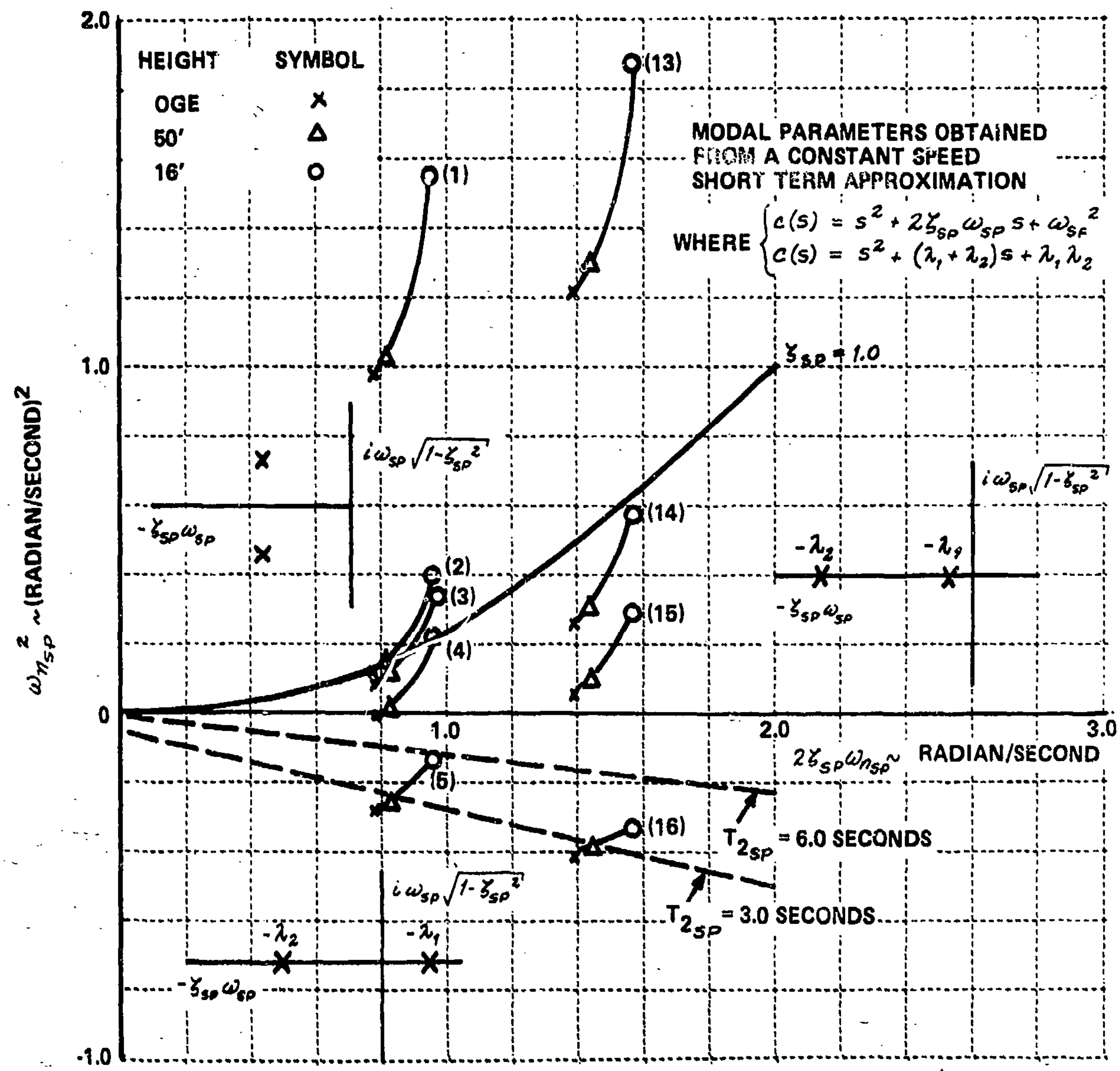


Figure 5 SHORT PERIOD MODAL PARAMETERS IN AND OUT OF GROUND EFFECT

Thus the short period approximation generally predicts a more stable configuration than that obtained from the full characteristic equation.

TABLE II

COMPARISON OF SHORT PERIOD APPROXIMATION ROOTS WITH COMPLETE CHARACTERISTIC EQUATION ROOTS (OUT OF GROUND EFFECT)

CONF.	λ_1	$\frac{1}{T_{SP_1}}$	λ_2	$\frac{1}{T_{SP_2}}$
2	.1900	.1926	.5920	.6328
3 (6)(8)	.1107	-.0855	.6714	.7030
4 (7)(9)	-.0186	-.1656	.8006	.8220
5	-.2661	-.3446	1.0479	1.0560
10	.1107	-.0710	.6714	.6725
11	-.0186	-.1497	.8006	.7997
12	-.2661	-.3291	1.0479	1.041
14 (17)	.2091	-.0840	1.1842	1.186
15 (18)	.0348	-.1654	1.3584	1.354
16 (19)	-.2509	-.3465	1.6441	1.631

NOTE: Negative values of λ_1 and $1/T_{SP_1}$ indicate an unstable real root (aperiodic divergence).

2.5 INFLUENCE OF SPEED INSTABILITY (BACKSIDEDNESS)

Several of the configurations evaluated in this program were specifically designed with reduced levels of induced drag (out of ground effect) to examine the effects of "speed instability" (or backsidedness, Appendix II) on pilot rating in the landing approach task for large delta-wing transports. For all configurations evaluated in this program, the ground effect reduces "backsidedness" by decreasing induced drag and increasing the lift curve slope. Reference 2 indicates that a change in $d\gamma/dV$ from .069 degrees/knot to 0.0 degrees/knot for configurations with zero static margin ($M_\alpha = 0$) but statically stable ($\omega^2_{n_{SP}} > 0$) did not significantly affect pilot rating for two of the three evaluation pilots used in that program. The airplane configurations to be evaluated in this program were designed to examine this effect for various values of M_α. The $d\gamma/dV$ variations are of a similar order of magnitude to that used in the above reference. This variation covers the Level 1 and Level 2 regions for flight path stability of Reference 3.

2.6 INFLUENCE OF GROUND EFFECT

The configurations evaluated in this program include the influence of ground effect based on the data package supplied by the FAA. Section III of Volume II of this report illustrates the functional form of the ground effect. This functional form was not changed during the in-flight evaluation for all the aerodynamic stability and control derivatives except that the influence of ground effect on the pitching moment equation was reduced as C_{m_α} was made more positive (unstable) based upon the equivalent c.g. location (Reference 4). The ground effect used tends to follow the preferred form discussed in Reference 4, that is, the lift change tends to lead the pitching moment change. As previously shown on Figure 5, the short term modal parameters are not significantly altered by the ground effect until the height of the airplane c.g. is within 50 feet of the runway. As shown in Volume II of this report, based on a quasi-steady trajectory analysis, a c.g. height of 50 feet is the altitude at which the pilot would be required to introduce significant elevator trim changes. These trim changes must occur in a relatively short time to counter the nose-down tendency of the ground effect in order to maintain an approximately constant attitude approach and touchdown. The data presented in Reference 4 indicates that an increase in the magnitude of elevator stick force associated with the landing flare maneuver in ground effect can have a significant degrading influence on pilot rating as static stability is reduced. Pilot workload parameters in terms of the primary frequency of elevator control input and elevator column force for the configurations evaluated in this program are presented in Section IX of Volume II of this report.

2.7 LANDING APPROACH TRAJECTORY ANALYSIS

References 4 and 5 both examined the landing flare maneuver of large transport aircraft in the presence of ground effect, and both conclude that the ability of the pilot to maintain a constant pitch attitude is critical to landing the aircraft. Thus the ability of the pilot to compensate the strong nose-down pitching tendency by coordination of elevator inputs may be the most demanding portion of the entire landing task. As an estimate of the importance of compensation for ground effect by elevator for the landing maneuver at constant approach speed, a quasi-steady trajectory analysis was performed for the configurations evaluated in this program. Specific details of this analysis are presented in Section V, Volume II of this report. The results of this analysis may be summarized as follows: (1) for all configurations evaluated in this program, maintaining the attitude required for a glide slope of 2.5 degrees would land all configurations at rates of descent below 2 feet/sec except for configurations 5, 12, 16, 19; (2) configurations 5, 12, 16, 19 would tend to balloon in height without achieving touchdown unless the pitch attitude was allowed to decrease prior to touchdown. Thus for these configurations, the pilot would be required to use elevator in a method contrary to what could be considered normal in the flare and touchdown task for the other configurations evaluated in this program. For all configurations, the analysis indicates that significant elevator compensation would be required for approximately the last ten seconds of the approach (as wheel height reduces from 35 feet above the runway to touchdown).

SECTION III

DESCRIPTION OF EXPERIMENT

3.1 EQUIPMENT

The flight evaluations of this program were flown in the Air Force Total In-Flight Simulator (TIFS) operated by Calspan. A layout diagram of TIFS is shown in Figure 6.

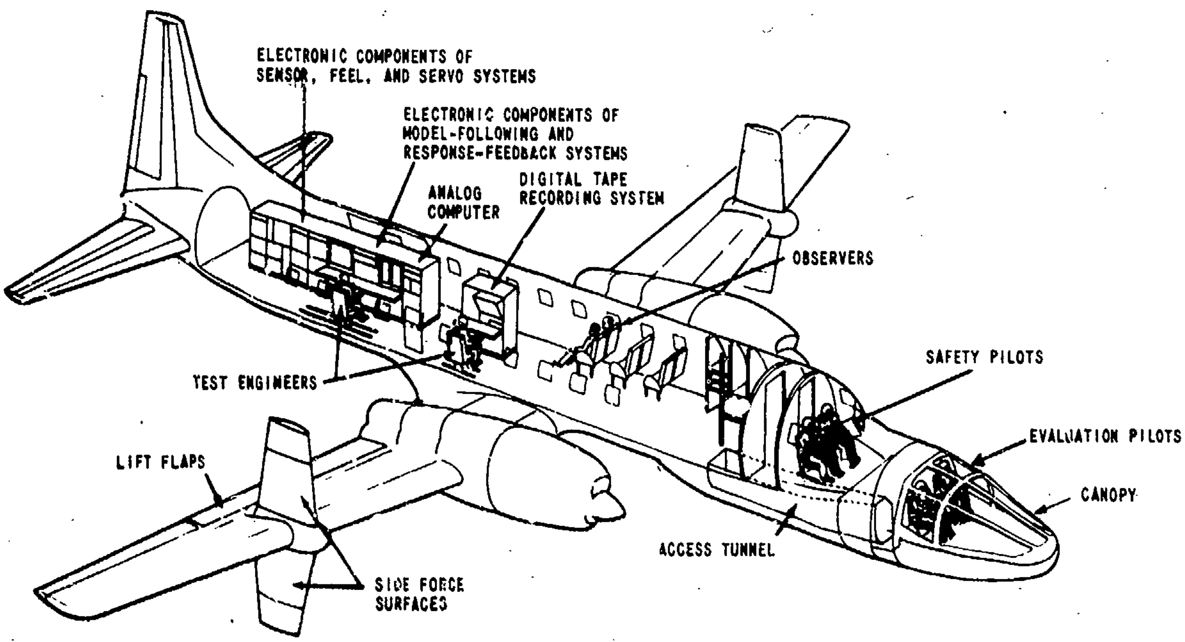


Figure 6 LAYOUT OF TOTAL IN-FLIGHT SIMULATOR (TIFS)

For this program, the TIFS was operated in the model-following simulation mode; a block diagram illustrating this mode is presented in Figure 7. The TIFS development, design and fabrication are described in Reference 6. The detailed capabilities of TIFS are completely outlined in Reference 7. The TIFS simulation cockpit, occupied by the evaluation pilot, is a completely separate cockpit mounted on the nose of the NC-131H to give the evaluation pilot as much of the simulated aircraft environment as possible. The instrument panel used for this evaluation included the instruments developed under the PIFAX program (Pilot Factors Program sponsored by the FAA and performed under Air Force direction). The two primary instruments are an Attitude Director Indicator (ADI) Model 4058-E and a Horizontal Situation Indicator (HSI) Model AQU-4. In this landing approach flight evaluation, the task included ILS approaches performed either in actual IFR weather conditions or under simulated IFR conditions with the evaluation pilot wearing a hood. The ILS approaches were accomplished using the raw glide slope indicator on the ADI and the raw localizer needle on the HSI. The flight director horizontal and vertical steering needles on the ADI were removed from the sight of the evaluation pilot.

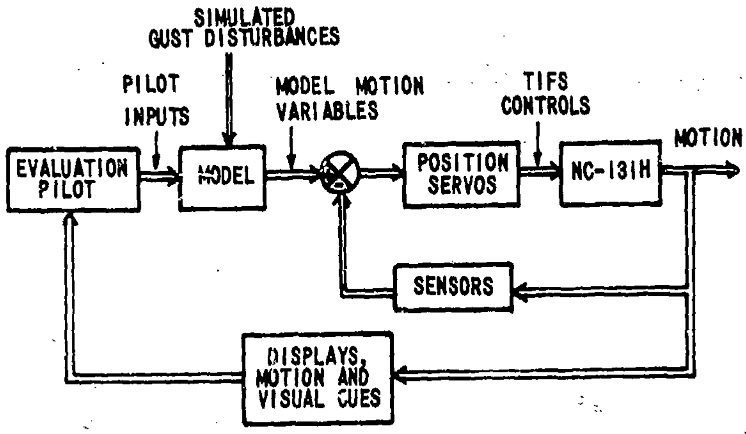


Figure 7 MODEL-FOLLOWING MOTION SIMULATION

Another change to the ADI was a modification that provided double the pitch sensitivity of the normal presentation. In other words, each degree of pitch angle change of the model was represented as a two degree pitch change on the ADI. This was done to make the pitch display sensitivity comparable to that of a large delta-wing supersonic transport (e.g., Concorde). In addition to the two major instruments, other instruments included airspeed indicators (both digital and the normal round dial instrument), altimeter, engine instruments, clock, accelerometer, heading indicator, distance measuring equipment (DME) and vertical velocity indicator (VVI). The VVI was unique in that it provided instantaneous vertical velocity without the consequent lags associated with the usual pressure sensing instrument. Three other special instrument indications were presented on the panel in the simulation cockpit. A vertically moving tape indicating angle of attack, α , was displayed on the left side of the ADI. Another vertically moving tape showing wheel height was displayed on the right side of the VVI. A horizontally moving needle indicating sideslip angle, β , was located below the HSI. A photograph of the instrument panel (prior to the installation of the sideslip indicator) is shown in Figure 8.

The TIFS simulation cockpit is a two-place side-by-side arrangement with wheel controllers and rudder pedals. Elevator and aileron rate trim thumb buttons are located on the control columns and a toggle switch rudder trim is provided forward of the throttle console. Four throttles are located between the two seats on a center console. The evaluation pilot occupied the left seat during the evaluation flights.

Control feel to the wheel and rudder pedals was furnished by electrically controlled hydraulic feel servos which provide opposing forces proportional to the control wheel and rudder pedal deflection. The feel system

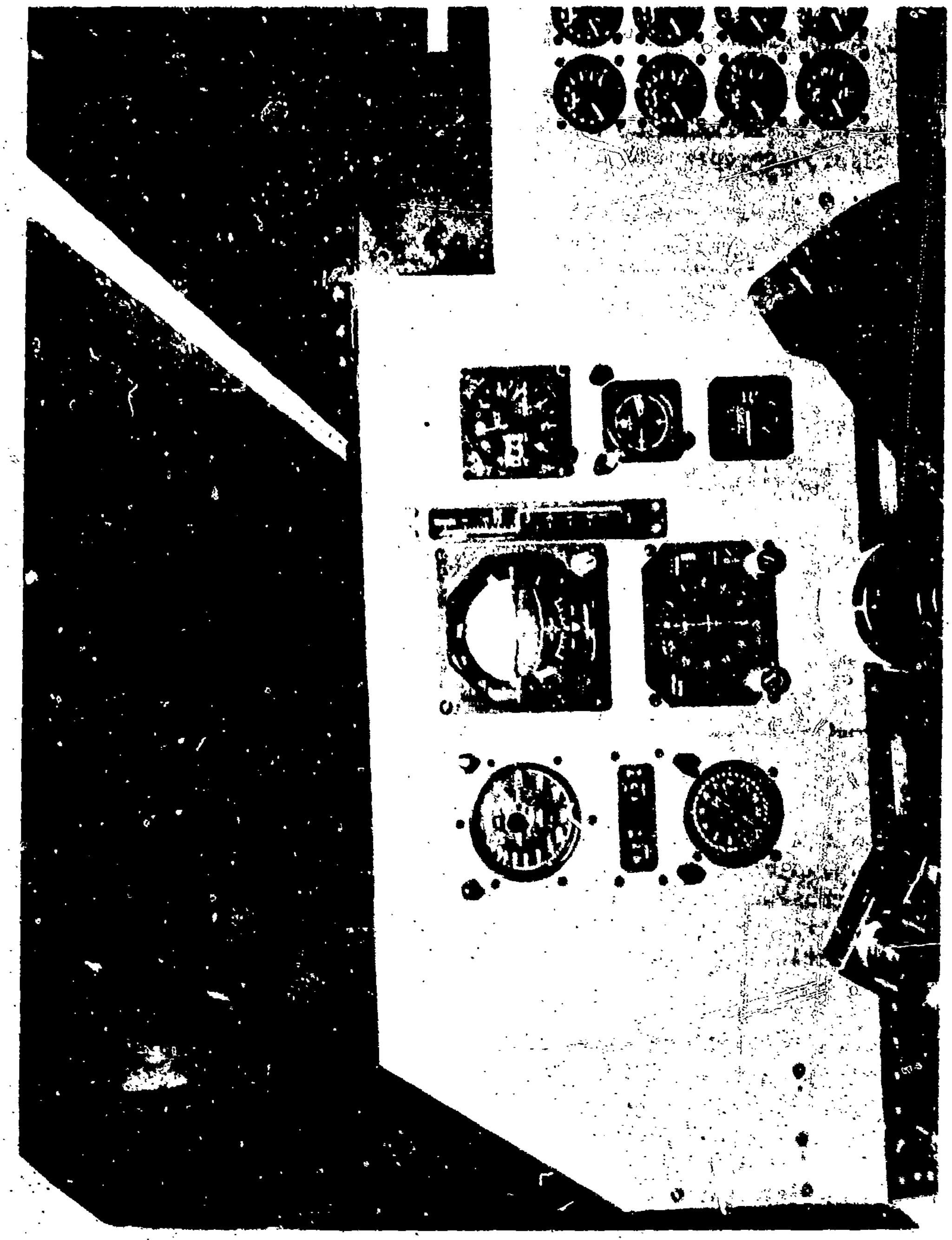


Figure 8 INSTRUMENT PANEL IN TIFS SIMULATION COCKPIT

dynamics for the elevator, aileron and rudder were held constant at the following values: $\omega_{n_{FS}}$ = 15 radians/second and ζ_{FS} = .85.

The elevator and aileron control system dynamics were represented as a second order system at a frequency of 32.9 radians/second and a damping ratio of unity. The rudder was represented with no control system lag.

The control system static characteristics were held constant throughout the evaluations at the values listed in Table III.

TABLE III

CONTROL GEARINGS AND FEEL SYSTEM CHARACTERISTICS

	Elevator	Aileron	Rudder
Force Gradient	11.0 lb/in.	.6 lb/deg	15.75 lb/in
Breakout Force	± 4.0 lb	± 2.0 lb	± 30 lb
Hysteresis	± .50 lb	± 2.0 lb	± 10 lb
Control Travel (max)	± 7 in.	± 46 deg	± 4 in.
Surface Travel	± 18 deg	± 18 deg	± 30 deg
Control Gearing	- 2.57 deg/in.	- .39 deg/deg	- 7.5 deg/in.
Trim Rate	.3125 in./sec	1.5 deg/sec	.133 in./sec

The engine dynamics were represented as a first order system with a 1.0 second time constant. Static thrust was mechanized as a linear gradient with zero thrust until 49% throttle and a maximum static thrust of 25,900 lb/engine at 100% throttle. Thus, the linear gradient used per engine was 508 lb/% throttle.

A touchdown signal was provided to the evaluation pilot in the form of a light located above the ADI and an aural indication on the interphone. In addition, a slight normal acceleration was generated by the sudden application of a down direct lift flap deflection when the computed wheel height reached zero. This computed wheel height gave the evaluation pilot the correct cockpit eye to ground height at touchdown. A radar altimeter provided the height information for the determination of touchdown, Figure 9.

For this program, the TIFS simulation included the very significant effect of flying a large delta-wing transport in close proximity to the ground. It thereby provided the evaluation pilot with the appropriate task when flying the simulated airplane in the final approach close to the ground. The complete ground effect was mechanized based on the data supplied by the FAA. The primary changes occurred to the pitching moment, lift and drag representations

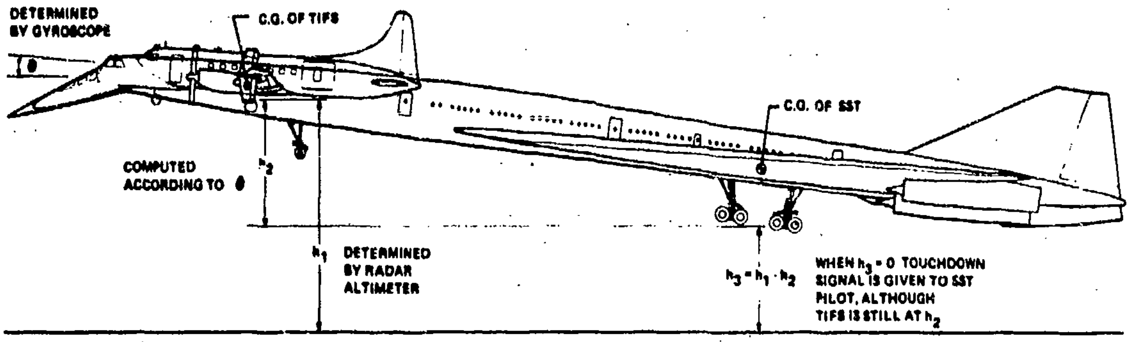


Figure 9 DETERMINATION OF TOUCHDOWN HEIGHT

but all six equations of motion were modified due to ground effect. The process involved in determining the simplified expressions that were used have been detailed in References 8 and 9. A summary of the modified equations is shown in Appendix I of this volume.

3.2 EVALUATIONS

3.2.1 Mission Definition

The evaluation mission was that of flying a large unaugmented transport airplane in the terminal task of IFR landing approaches to ILS minimums, followed by a day-time VFR approach to touchdown on a 10,000 foot runway. The evaluation pilot rating would be given considering an airline transport pilot performing a single pilot control task. It was assumed that there would be an additional pilot for monitoring and for overload cockpit duties. However, he would not assist either by moving the control column or by manipulating the throttles. Furthermore, it was assumed that the airline pilot was "well trained" (e.g., subjected to the training requirements of the FAA and to those of his own company), but that the training associated with flying the airplane with a complete augmentation system failure was administered infrequently. Therefore, there was no certainty that the pilot would have had recent experience in landing the unaugmented airplane.

It was agreed that a single Cooper-Harper pilot rating would be given for the mission (IFR approach and the VFR landing). Exceptions would be permitted for those situations where there might be an extreme variance between the difficulty of performing the flare and touchdown tasks as compared to flying the IFR approach. Then the pilot could give one rating for the approach and a separate rating for the flare and touchdown task, at his discretion.

3.2.2 Evaluation Procedure

Two evaluations were planned for each flight. Each evaluation included IFR approaches down to 300 feet above the ground. The remainder of the approach to touchdown was accomplished by visual reference to the real environment outside the cockpit. The majority of the ILS approaches were flown to runway 28R at Niagara Falls International Airport, Niagara Falls, New York. Some approaches were made to runway 5 at Greater Buffalo International Airport, Buffalo, New York because of the excessive tailwind component on the ILS approach at Niagara Falls. On one flight a series of approaches was made to runway 4 at the Monroe County Airport, Rochester, New York for the same reason as given above. The approach speed used for all approaches was 160 knots. The TIFS configuration for the approaches prior to engagement of the VSS when in level flight was landing gear down and both Fowler and direct lift flaps in the trail position. These flap settings produced approximately 10 degrees angle of attack mismatch with the model at the initial condition of VSS engagement. The mismatch was accounted for in the transformation of the model equations of motion as shown in Appendix II causing the TIFS cockpit motion to match the model's cockpit motion although differing in incidence by a constant 6 degrees.

For this experiment the TIFS gust alleviation system was not used because it was not fully optimized. A model-following variable stability system will tend to act as a limited bandwidth gust alleviation system when no turbulence inputs are fed to the model and the feedforward and feedback signals are inertial quantities. In this situation the turbulence response experienced by the evaluation pilot is that portion of the normal TIFS airplane turbulence response not alleviated by the model-following loops. For those approaches where the natural turbulence level was greater than moderate, no inputs were fed to the model. On other approaches, either the sensed natural turbulence or a combination of natural and canned turbulence was fed to the model. The blending of natural and artificial turbulence was accomplished electronically (Section IX of Volume II) whenever the sensed natural turbulence was less than the prescribed level. Then, canned turbulence was inserted to raise the turbulence to the amount designated for the particular task. The canned turbulence model was based on the Dryden spectral form of MIL-F-8785B(ASG) with $L_{u,v} =$ 1000 ft. Details of the canned turbulence simulation are presented in Reference 10.

A total of 61 evaluations of 20 different configurations was performed by four evaluation pilots. This total included two repeats each of the same configuration by Pilots A and B. Four evaluations were repeated by Pilot D. The entire program was split up so that Pilots A, B, C and D performed 19, 15, 6 and 31 evaluations, respectively.

The evaluation pilots were not informed about the configurations to be evaluated on any flight.

3.2.3 Evaluation Tasks

A typical sequence of tasks during each evaluation was as follows:

1. Familiarization with the configuration

   (a) Determine trimmability -- ease of achieving trim and the behavior 10 - 20 knots off trim airspeed.

   (b) Perform maneuvering as considered necessary to determine ability to make precise pitch, airspeed and heading changes. A wind-up turn to at least 1.4g was included if it appeared there might be a problem with flaring the airplane.

2. IFR approach (simulated by use of a hood)

   (a) Radar vectored track on a 30 degree intercept of the ILS final approach course.

   (b) Localizer acquisition a few miles outside the outer marker.

   (c) Localizer tracking and glide slope acquisition and tracking down to an altitude of 300 feet above the ground.

3. Visual final approach to touchdown.

The IFR approach was planned with three distinct variations as follows:

1. TASK A was a straight-in approach with a turbulence level, σ, of 0.5 feet/second when no natural turbulence existed.

2. TASK B included a glide slope error of one dot (up or down) from the outer marker to an altitude of 800 feet above the ground. It also included a 90 degree crosswind component of 15 knots that was inserted after localizer interception and remained in until touchdown. As in Task A, a turbulence level, σ, of 0.5 feet per second was provided whenever the air was too smooth.

3. TASK C consisted of a localizer offset error of one dot that was inserted prior to localizer acquisition. This error remained until 200 feet above the ground. It produced approximately a 200 foot lateral offset at the middle marker. In addition, a turbulence level with a σ = 3 feet per second was provided if the level of natural turbulence was not sufficiently high.

Task A was always given first but the order of the other two tasks was interchanged at random. The evaluation pilots were not informed as to which task they would be subjected to after the initial approach.

Details of the mechanization of the glide slope and localizer offsets, the artificial crosswind and the addition to the natural turbulence level are described in Section IV of Volume II.

3.2.4 Pilots

Four evaluation pilots participated in the program. Prior to the evaluation of the configurations in the TIFS airplane, all evaluation pilots participated in a ground simulation evaluation program. This program evaluated the configurations designed for the in-flight program on the Ames Flight Simulator for Advanced Aircraft (FSAA) Reference 11. The initial flight for each pilot in the in-flight investigation program was a pre-evaluation flight that allowed the pilot to become familiar with the TIFS airplane, the in-flight evaluation procedure and the use of the pilot comment card. Two configurations were flown by the evaluation pilots during this flight. One was a stable configuration (either configuration number 1 or 20) and the other was a mildly unstable configuration that was also on the backside of the power required curve. This combination of configurations allowed the pilots to see the difficulty of controlling a stable configuration that suddenly became even more stable prior to touchdown and also permitted them to see one of the unstable configurations before their first actual evaluation.

A summary of the evaluation pilots' general flight experience is presented below:

Pilot A: USAF pilot and graduate of the USAF Test Pilot School with extensive experience in flight test. He has a total of approximately 9500 hours with the majority of that time being in large aircraft. He has flown several flights in one of the Concorde prototype aircraft.

Pilot B: NASA Ames research pilot who served as project pilot on various handling qualities studies using both aircraft and ground simulators. His flight experience of 7000 hours includes many experimental V/STOL aircraft, rotor craft, fighter and large jet transport aircraft.

Pilot C: FAA test pilot with approximately 6000 hours of flying time. This experience has been obtained in an extensive variety of small and large airplanes and helicopters.

Pilot D: Calspan research pilot with extensive experience as an evaluation pilot in handling qualities investigations using variable stability aircraft and ground simulators. His flight experience of 5500 hours is distributed over a wide variety of aircraft types.

3.2.5 Pilot Comment and Rating Data

Pilot comments and ratings were the primary data obtained. In order to standardize the order and organization of the pilot comments, the evaluation pilots were encouraged to use the Pilot Comment Card which is reproduced as Table IV.

The evaluation pilot was requested to comment on the items listed on the comment card at the completion of each evaluation. However, he was free also to comment at any time during the evaluation when he felt it appropriate. One of the pilots chose to make comments at the completion of each approach while the TIFS was being flown outbound by the safety pilots prior to setting up the aircraft for a subsequent approach. As indicated by Item 16 on the comment card, the pilot was asked to assign a pilot rating for the configuration after completing the comments. This rating was given by the pilot in accordance with the Cooper-Harper Handling Qualities Rating Scale as described in Reference 12 and shown in Figure 10.

The pilot rating assigned by the evaluation to each configuration included the effects that turbulence had on the handling qualities. Therefore, in addition to the rating of the overall configuration, an alphabetical rating was assigned which was an assessment of the effects of turbulence on the handling qualities. These ratings were given in accordance with the turbulence effect rating scale shown in Figure 11 which has been used by Calspan in other flight research programs. The use of the turbulence effect rating scale allows an estimation to be made of the degradation in pilot rating for a given configuration in the landing approach as a function of turbulence effect. However, one serious drawback with this rating system was the difficulty that the evaluation pilot had in choosing a rating when he did not have the opportunity of making at least one approach in smooth air.

TABLE IV

PILOT COMMENT CARD

1. Ease of achieving trim.

2. Any objectionable behavior off trim airspeed.

3. Maneuvering about level flight:

   attitude control, altitude control, airspeed control, etc.

4. Maneuvering in turning flight:

   lateral control, altitude (and pitch) control, airspeed control, maneuvering forces. (Acceptability for mission), "g"

5. Localizer acquisition and tracking prior to glide slope interception:

   a. performance capability

   b. workload

   c. effect of localizer task on altitude performance.

6. Glide slope acquisition:

   a. control techniques to acquire (elevator and throttle)

   b. performance capability

   c. workload.

7. Tracking of glide slope and localizer:

   a. ability to maintain and re-acquire glide slope; control of airspeed?

   b. ability to maintain and re-acquire localizer

   c. does your pitch task affect heading control adversely?

   d. describe any unusual use of the display

   e. control technique: elevator and throttle used to control what?

   f. describe input required to produce desired pitch response

   g. how suitable to the task is the resulting airplane motion?

   h. does the airplane feel as though it is trying to get away from you unless you are continually and consciously controlling it?

8. Ability to correct lateral offset errors on breakout. Did the required maneuvering adversely affect your control of landing touchdown point or sink rate?

9. Control technique, power management, performance, workload in flare and touchdown maneuver.

10. Crosswind landing:

    a. difficulty

    b. wing down or decrab technique?

    c. effect on sink rate and touchdown point control.

11. Control feel: elevator, aileron, rudder

    a. forces to produce desired response

    b. control travel

    c. breakout forces

    d. friction.

12. Throttle control feel, friction.

13. Which of the required evaluation tasks was most degraded by the configuration characteristics?

14. Turbulence effects - has rough air brought out any characteristics that would affect your ability to fly this configuration?

15. Could you continue to fly this configuration for 30 minutes in turbulence doing landing approach tasks?

16. Configuration rating.

17. Turbulence effect rating.

18. Summarize primary reasons for ratings:

    a. what was the most objectionable feature of the configuration?

    b. what was the least objectionable or best feature of the configuration?

19. Were there any simulation malfunctions during the evaluation?

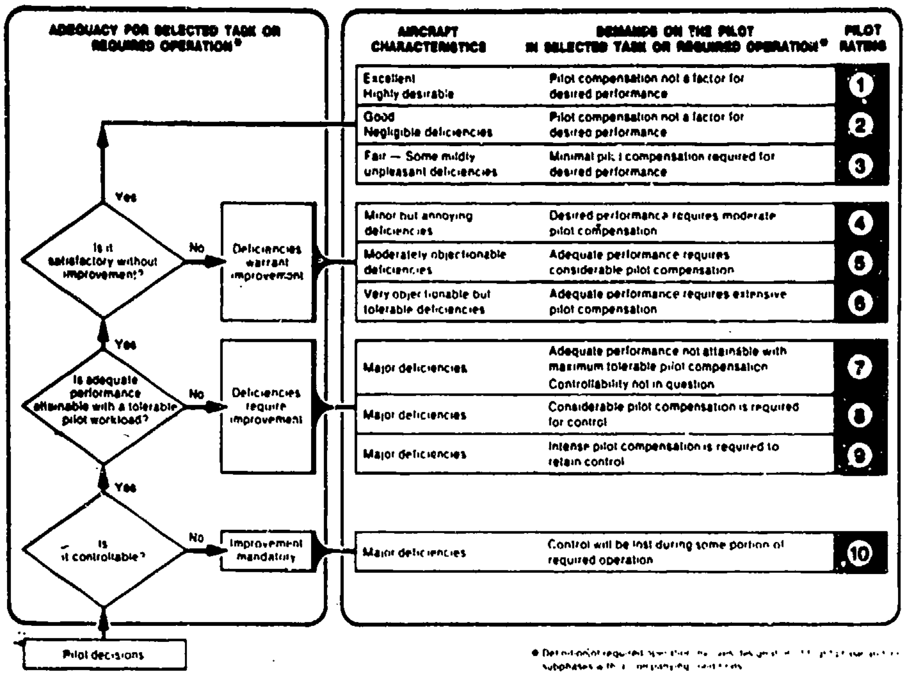


Figure 10 COOPER-HARPER HANDLING QUALITIES RATING SCALE

INCREASE OF PILOT EFFORT WITH TURBULENCE	DETERIORATION OF TASK PERFORMANCE WITH TURBULENCE	RATING
NO SIGNIFICANT INCREASE	NO SIGNIFICANT DETERIORATION	A
MORE EFFORT REQUIRED	NO SIGNIFICANT DETERIORATION	B
	MINOR	C
	MODERATE	D
BEST EFFORTS REQUIRED	MODERATE	E
	MAJOR (BUT EVALUATION TASKS CAN STILL BE ACCOMPLISHED)	F
	LARGE (SOME TASKS CANNOT BE PERFORMED)	G
UNABLE TO PERFORM TASKS		H

Figure 11 TURBULENCE EFFECT RATING SCALE

3.2.6 Model Validation Procedure

When using a model-following type of variable stability airplane for research, the verification that a particular dynamic configuration is being flown consists of checking two basic items:

(1) Ascertaining that the correct model has been set up on the analog computer, i.e., the potentiometers defining stability derivatives were set correctly, and that the analog was producing the correct time histories for selected control inputs.

(2) Ascertaining that the TIFS responses in flight were in fact following the analog generated responses for pilot control inputs.

Item 1 was accomplished in the following ways:

a. A static voltage check was performed on the analog representation to verify proper mechanization of the equations of motion.

b. Nonlinear six-degree-of-freedom digital computer time histories of model responses to control inputs were compared with those generated for identical control inputs by the model analog computer. This comparison was simplified by producing time history overlays from the digital computer responses which were then used to compare with the time histories generated by the VSS model analog and recorded on the on-board strip chart recorder.

c. Trim values of V_T , θ_T and [illegible] were set in as initial conditions to the model analog computer and the model allowed to achieve trim through balance loops. The trim values of C_L , C_D , C_m , δ_e and T_m were compared with the nonlinear six-degree-of-freedom digital computations.

d. To verify that the correct ground effect mechanization was incorporated, Step c was repeated at model wheel heights of 2, 11, 36, 86 and 186 feet above ground level, and compared to data generated at NASA Ames (Reference 11).

Item 2 was achieved as follows:

a. While using only the model computer on board, model computer responses recorded on the strip chart were compared with the digital computer time history overlays. The θ , V , α and $\dot{\alpha}$ responses for both δ_e and ΔT step inputs were compared as were the ϕ , p , β and r responses for both δ_a and δ_r step inputs. These procedures were accomplished prior to the evaluation of each configuration.

b. After item 2a was verified, TIFS model-following responses to pilot control inputs were similarly compared.

c. Continuous monitoring of the model following was performed by Test Engineer No. 1 during the evaluation flying.

3.3 DATA ACQUISITION EQUIPMENT

The TIFS airplane is equipped with the following data acquisition equipment:

1. Four-channel Brush strip chart recorder.
2. Sixty-channel Ampex digital magnetic tape recorder.
3. Two Norelco cassette tape voice recorders.

The strip chart recorder, which incorporates the ability to select 10 different combinations of 4 output channels, was used continuously in flight to monitor model-following system performance. The digital magnetic tape recorder was used to acquire specific documentation records of responses to classic inputs and records of aircraft response and control activity on the ILS approaches flown during the evaluation for more detailed analysis after the flight. Typical time histories are presented in Appendix III of this volume. Specific data recorded on the magnetic tape recorder are listed in Appendix I of Volume II.

One voice recorder was used exclusively to record the comments of the evaluation pilot while the other was available when required to record pertinent TIFS crew intercommunications pertaining to model-following system and general airplane operation.

SECTION IV

DISCUSSION OF RESULTS OF THE IN-FLIGHT INVESTIGATION

4.1 PILOT RATINGS AND PILOT COMMENTS

Table V presents a summary of the pilot ratings for the various configurations evaluated in this research program. Included in the table is a general description of the configuration in terms of C_{m_α}, backsidedness, and ($C_{m_{\dot{\alpha}}} + C_{m_q}$). The time to double amplitude (T_2) computed from the unstable aperiodic root of the linearized longitudinal characteristic equation is also presented. Repeat evaluations appear in brackets. Turbulence effect rating is presented with the pilot rating. For those configurations where the pilot gave two distinct ratings for both the approach task and the flare and touchdown task of the mission, these ratings have been separated by a semicolon.

The full evaluation pilot comments are presented in Section VI of Volume II of this report. A summary of these comments, describing the primary piloting difficulties, are presented by configuration number in Section 4.5.

The following general observations can be made based upon the pilot comments and ratings obtained in this program for the statically unstable configurations. A typical time history of control activity in the approach task is presented in Appendix III of this volume.

(1) Tight attitude control was required to fly the mission for all configurations. Specifically in flare and touchdown, pilots tended to use large pumping motions of the elevator. In addition, pilot commentary indicates that pitch rate cues were used to provide the lead required to control attitude and flight path.

(2) The nose down pitching moment associated with ground effect coupled with the sluggishness of the airplane response to elevator inputs significantly affected pilot opinion of the configurations. For most of the configurations evaluated, the pilot rating reflects control difficulties in the flare and touchdown task. This observation was emphasized when the evaluation pilot separated the approach rating from the flare and touchdown rating.

(3) On several approaches, the degrading influence of ground effect could be reduced by ducking under the normal glide slope and then flying a shallower flight path angle prior to touchdown. Insufficient data are available to determine the effect of this technique on pilot opinion of the acceptability of a configuration for the landing mission.

(4) As the level of instability was increased, pilot rating degraded and the effect of turbulence on pilot workload and task performance became more significant.

Table V

SUMMARY OF PILOT RATINGS

CONF.	C_{m_α}	$d\gamma/dV$	$C_{m_{\dot\alpha}} + C_{m_q}$	T_2	PILOT RATINGS			
					A	B	C	D
1	LINEAR	BACKSIDE	NOMINAL	STABLE	—	2C	2B	5D
2	LINEAR	BACKSIDE	NOMINAL	59.6	4D	7; 10 (5; 8)	—	6-7
3	LINEAR	BACKSIDE	NOMINAL	8.12	6-7D	6	9; 10F	5; 6D
4	LINEAR	BACKSIDE	NOMINAL	4.17	5C	5; 7D	—	7-8E
5	LINEAR	BACKSIDE	NOMINAL	2.0	10E	—	10; 10F	7D (10F)
6	NONLINEAR (1)	BACKSIDE	NOMINAL	8.12	5C (4.5C)	5; 10 (6)	6; 8D	8C (6D)
7	NONLINEAR (1)	BACKSIDE	NOMINAL	4.17	6E	7; 8C	6D	9F (7D)
8	NONLINEAR (2)	BACKSIDE	NOMINAL	8.12	5A	7; 8D	—	5C
9	NONLINEAR (2)	BACKSIDE	NOMINAL	4.17	6.5D	6	—	7 (5.5C):)
10	LINEAR	BOTTOM	NOMINAL	9.73	5D	5; 9C	—	7D
11	LINEAR	BOTTOM	NOMINAL	4.61	5D (6B)	—	—	6D
12	LINEAR	BOTTOM	NOMINAL	2.10	10F	6-7; 10D	—	—
13	LINEAR	BACKSIDE	INCREASED	STABLE	3C	1-2	—	—
14*	LINEAR	BACKSIDE	INCREASED	8.21	4C	—	—	6D
15*	LINEAR	BACKSIDE	INCREASED	4.17	6B	—	5C	7.5D
16*	LINEAR	BACKSIDE	INCREASED	1.99	10E	—	—	10F
17*	NONLINEAR (2)	BACKSIDE	INCREASED	8.21	—	5; 8C	—	6D
18*	NONLINEAR (2)	BACKSIDE	INCREASED	4.17	6D	7; 10	—	—
19*	NONLINEAR (2)	BACKSIDE	INCREASED	1.99	—	—	—	10F
20	LINEAR	BOTTOM	INCREASED	STABLE	3C	—	—	4C

NOTE: ASTERISK INDICATES C_{m_α} MODIFIED TO MAINTAIN A SPECIFIED VALUE FOR TIME TO DOUBLE AMPLITUDE (T_2) AS ($C_{m_{\dot\alpha}}+C_{m_q}$) WAS INCREASED

REPEAT EVALUATIONS APPEAR IN PARENTHESES. WHEN APPLICABLE, THE FLARE AND TOUCHDOWN PILOT RATING IS DENOTED BY THE NUMBER FOLLOWING THE [illegible] COLON. FOR THE STABLE CONFIGURATIONS (1, 13, 20) THE [illegible] OF $C_{[illegible]}$ WAS [illegible] FROM .00342/deg TO .007/deg.

(5) For the backside configurations evaluated, airspeed control was a demanding piloting control task. When configurations were placed in the bucket of the power required curve by reducing the induced drag, pilot comments indicate a decrease in pilot workload associated with airspeed control on the approach. Pilot ratings, however, do not indicate a significant improvement in overall acceptability of the configuration for the mission.

(6) For the configurations with nonlinear pitching moment effects, the characteristic pitch-up tendency and increased instability associated with low airspeed/high angles of attack were considered objectionable. Attention to airspeed control was increased to avoid this objectionable behavior of the airplane.

(7) For those configurations with increased pitch damping (T_2 held constant), the pilot comments indicate that the associated delay in the appearance of the instability in attitude response was considered "insidious."

(8) The presence of a possible "learning curve" phenomenon appears evident by the general improvement in pilot rating and performance during the progress of the experiment. Each pilot exhibited some of this characteristic but Pilots B and D showed the greatest effects (see Figure 12). In general, until the pilots learned to control the airplane in ground effect, the pilot rating primarily reflected the extreme difficulties in attempting to land the airplane, rather than the influence of the variations in aerodynamic derivatives.

4.2 TOUCHDOWN PERFORMANCE DATA

Touchdown performance data obtained from the flight records are presented in detail by configuration, evaluation pilot and evaluation task in Volume II, Section VIII. Four of the parameters: rate of sink, touchdown distance, pitch attitude and touchdown airspeed, are presented as histograms on Figures 13 and 14. Figure 13 shows the variability in the parameters for each of the twenty configurations tested, whereas the information on Figure 14 shows the range in touchdown performance for each of the four pilots.

In general, there appears to be no single significant touchdown parameter which could be used as a correlator with the pilot ratings. Sink rate was definitely not a good indicator because for Configurations 5, 12, 16 and 19 (T_2 = 2 seconds), the touchdown sink rate rarely exceeded 5 feet per second. The only possible trend evident from the data was that when T_2 was decreased to 2 seconds, the touchdown distance was longer ($Y >$ 4000 feet) and the pitch attitude at touchdown was higher ($\theta > 13$ degrees). Also, at times, the touchdown airspeed was exceedingly low ($V <$ 135 knots). For those configurations, the pilot tended to permit degradation in all other parameters to achieve a reasonably low sink rate at touchdown. Since a rather limited data sample was obtained in this program, no attempt has been made to perform a statistical analysis of touchdown performance.

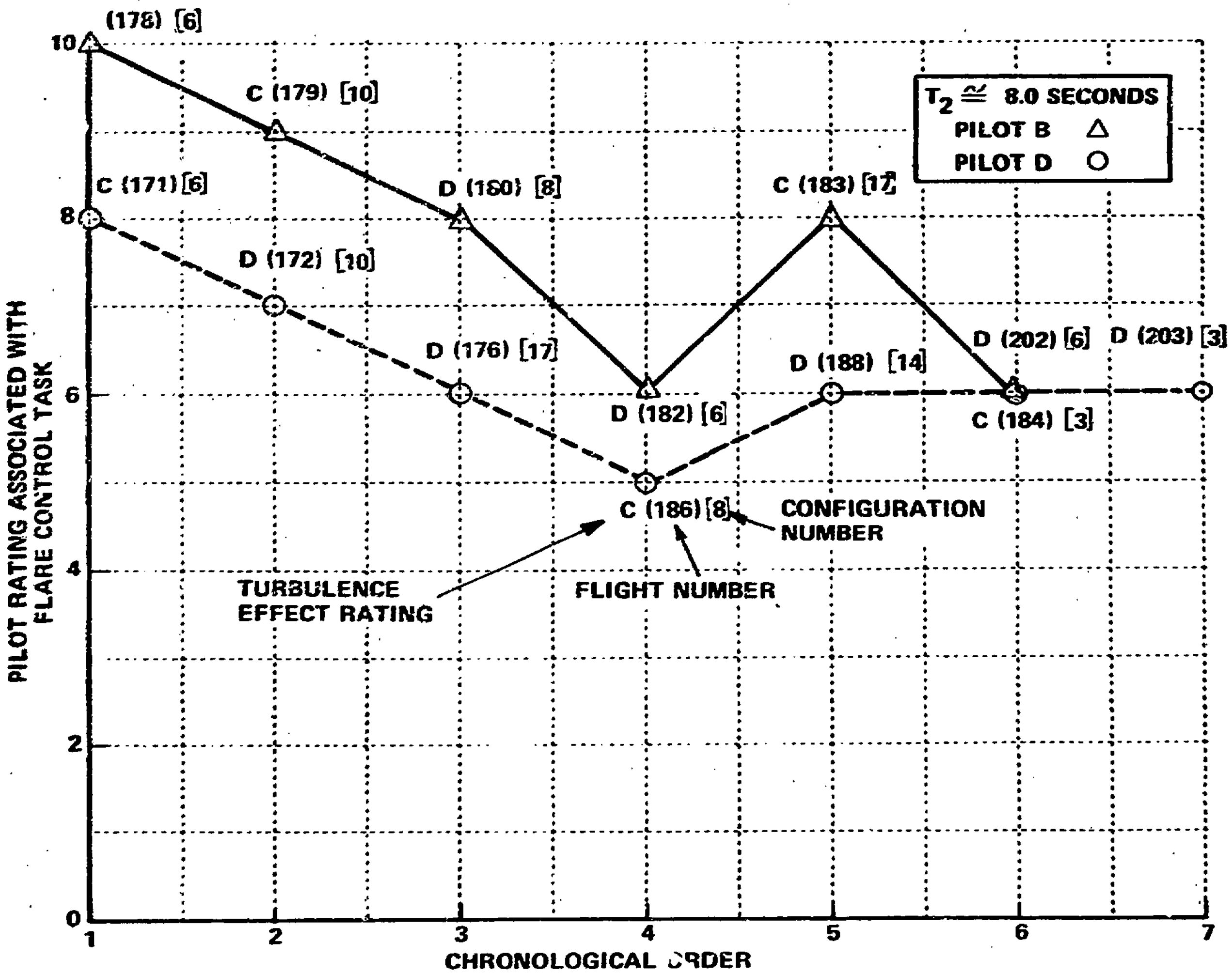


Figure 12 EXAMPLE OF POSSIBLE "LEARNING CURVE" PHENOMENON

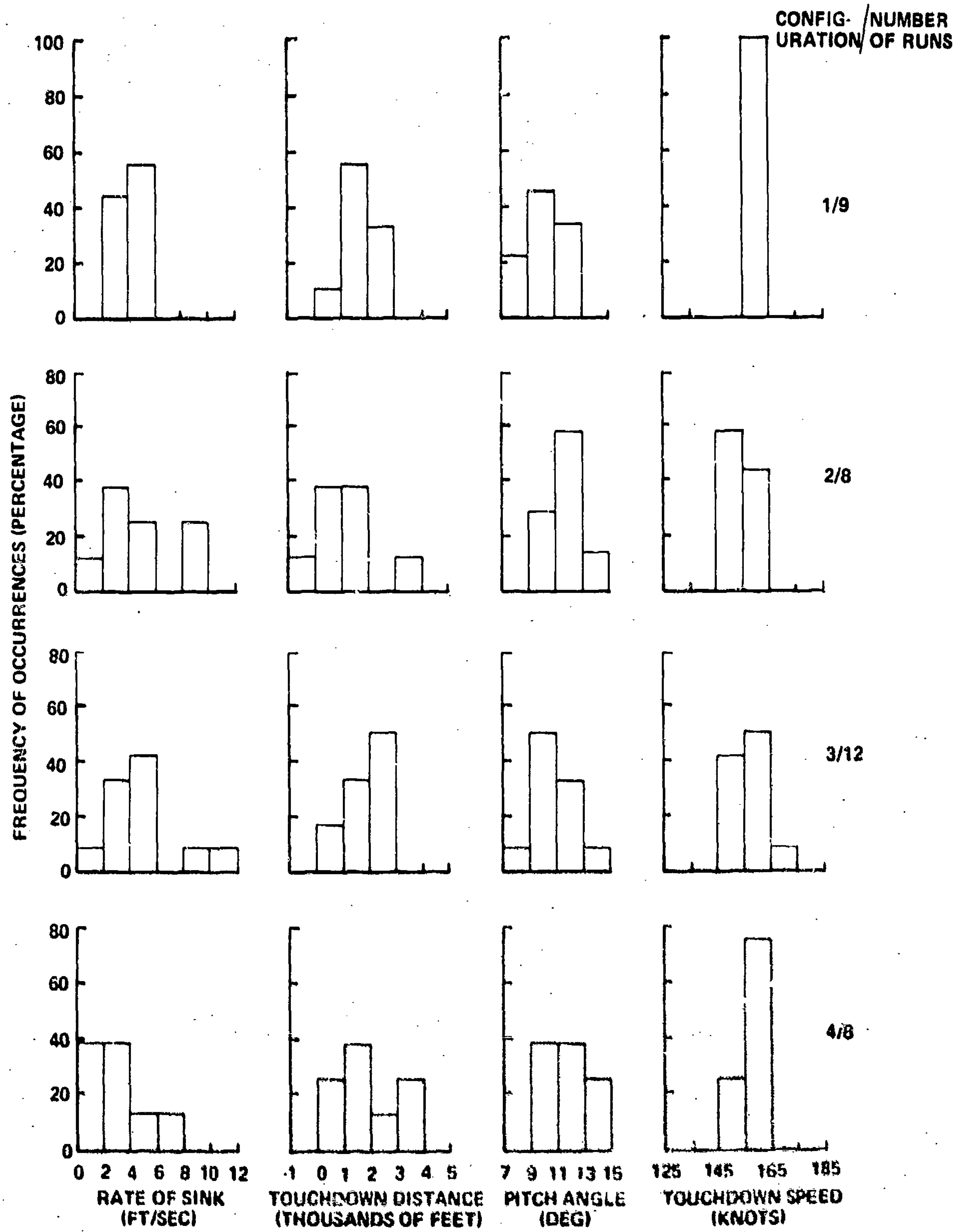


Figure 13 TOUCHDOWN PARAMETERS ACHIEVED BY ALL PILOTS FOR ALL CONFIGURATIONS

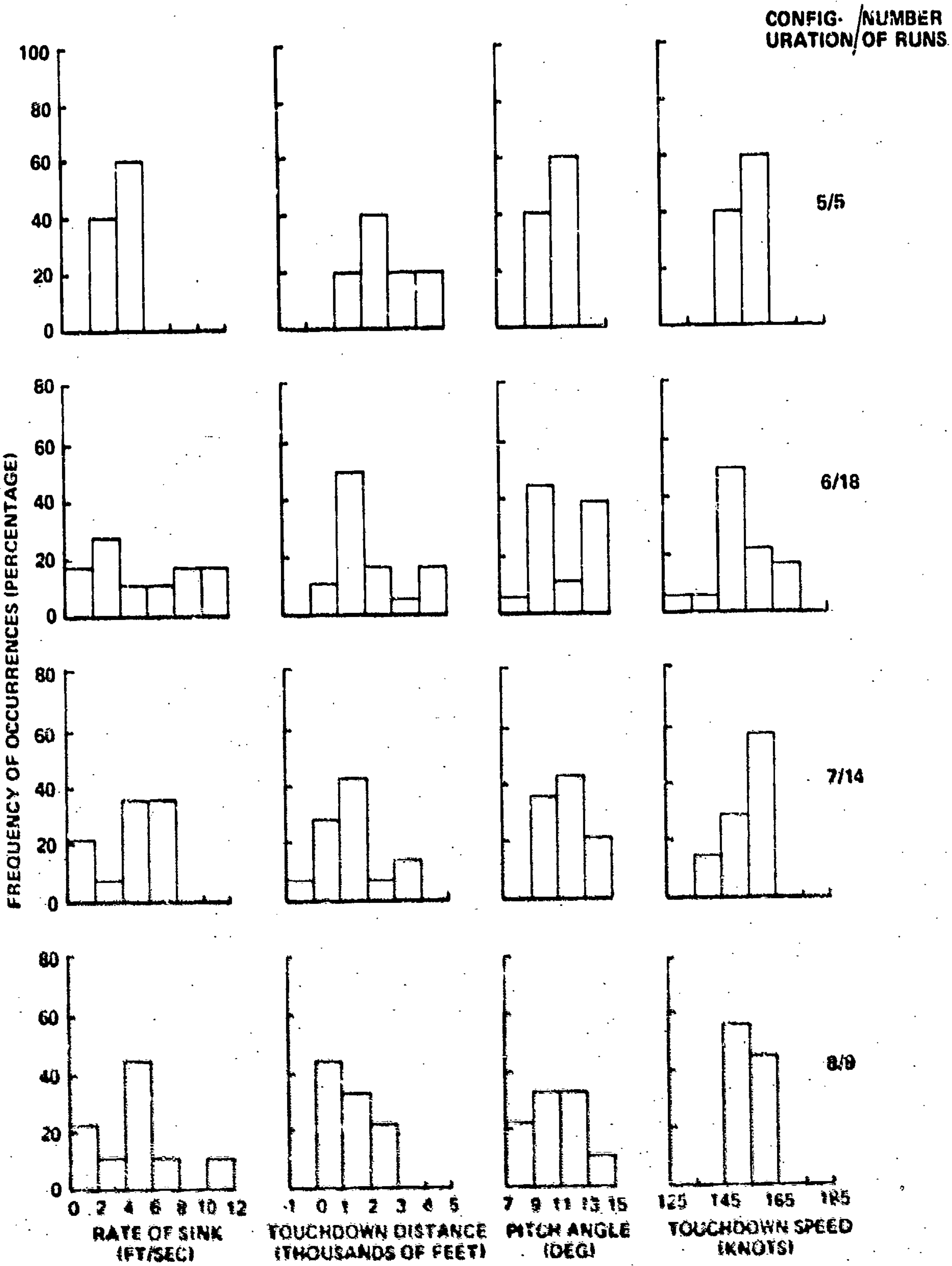


Figure 13 (cont.) TOUCHDOWN PARAMETERS ACHIEVED BY ALL PILOTS FOR ALL CONFIGURATIONS

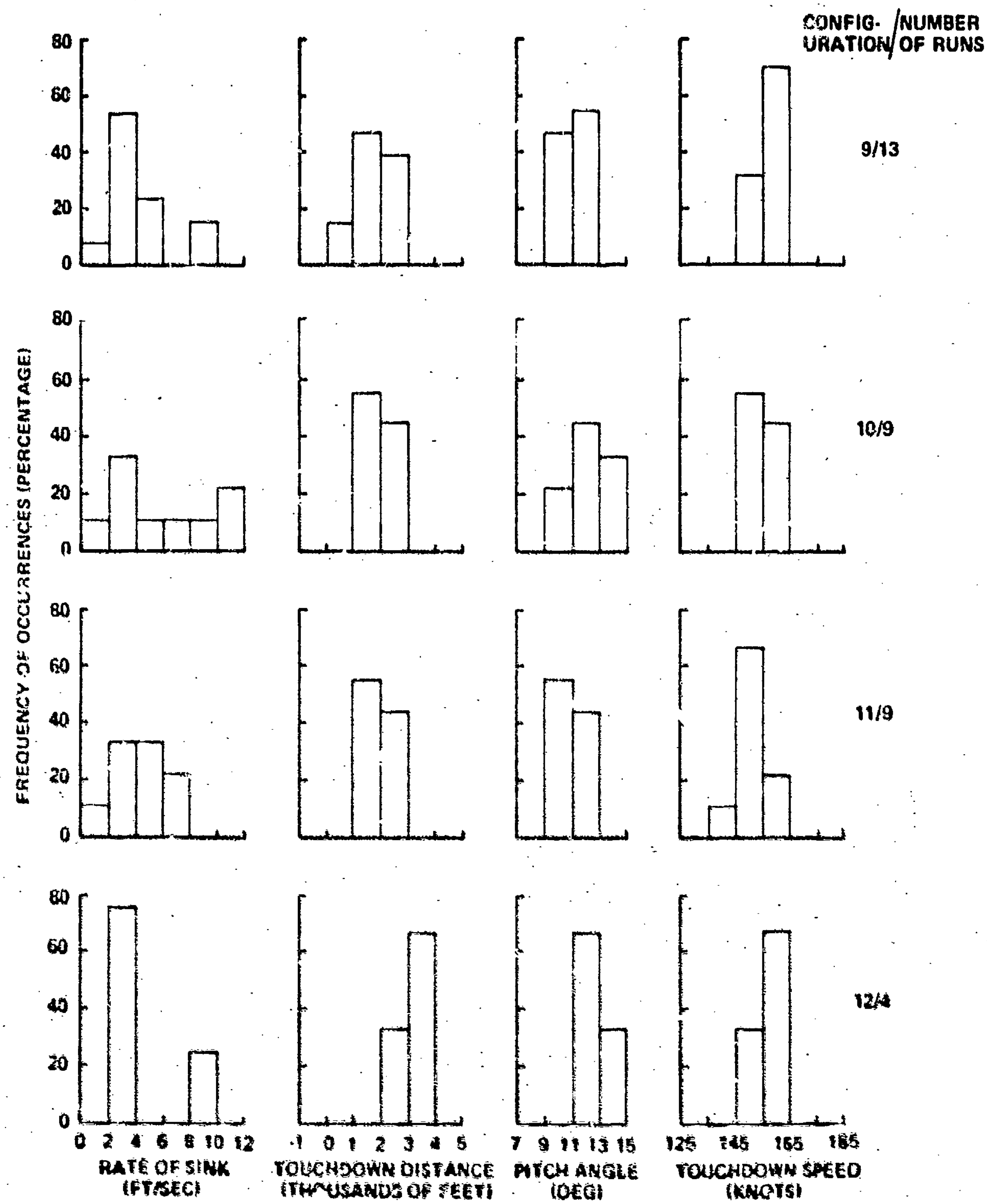


Figure 13 (cont.) TOUCHDOWN PARAMETERS ACHIEVED BY ALL PILOTS FOR ALL CONFIGURATIONS

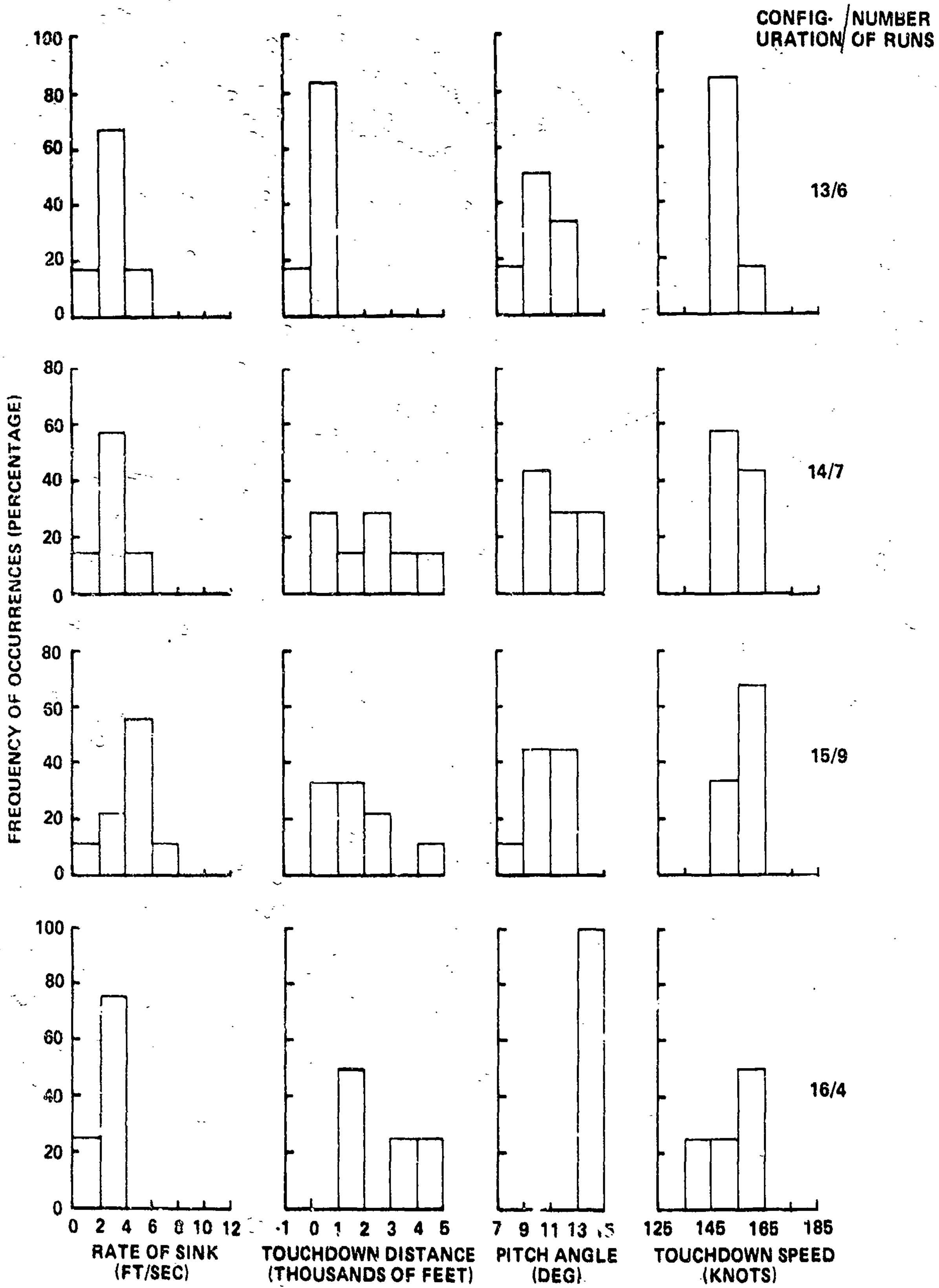


Figure 13 (cont.) TOUCHDOWN PARAMETERS ACHIEVED BY ALL PILOTS FOR ALL CONFIGURATIONS

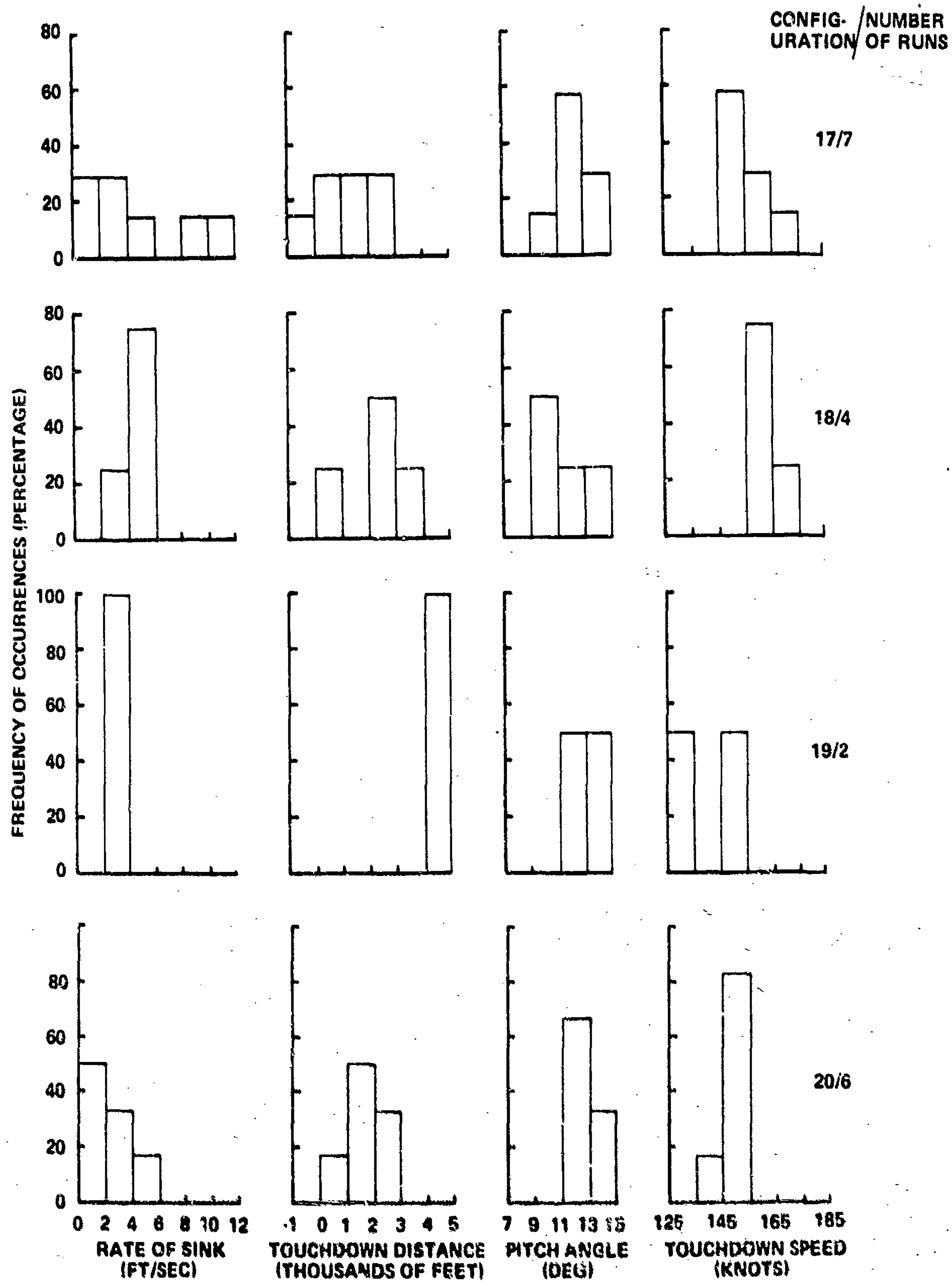


Figure 13 (cont.) TOUCHDOWN PARAMETERS ACHIEVED BY ALL PILOTS FOR ALL CONFIGURATIONS

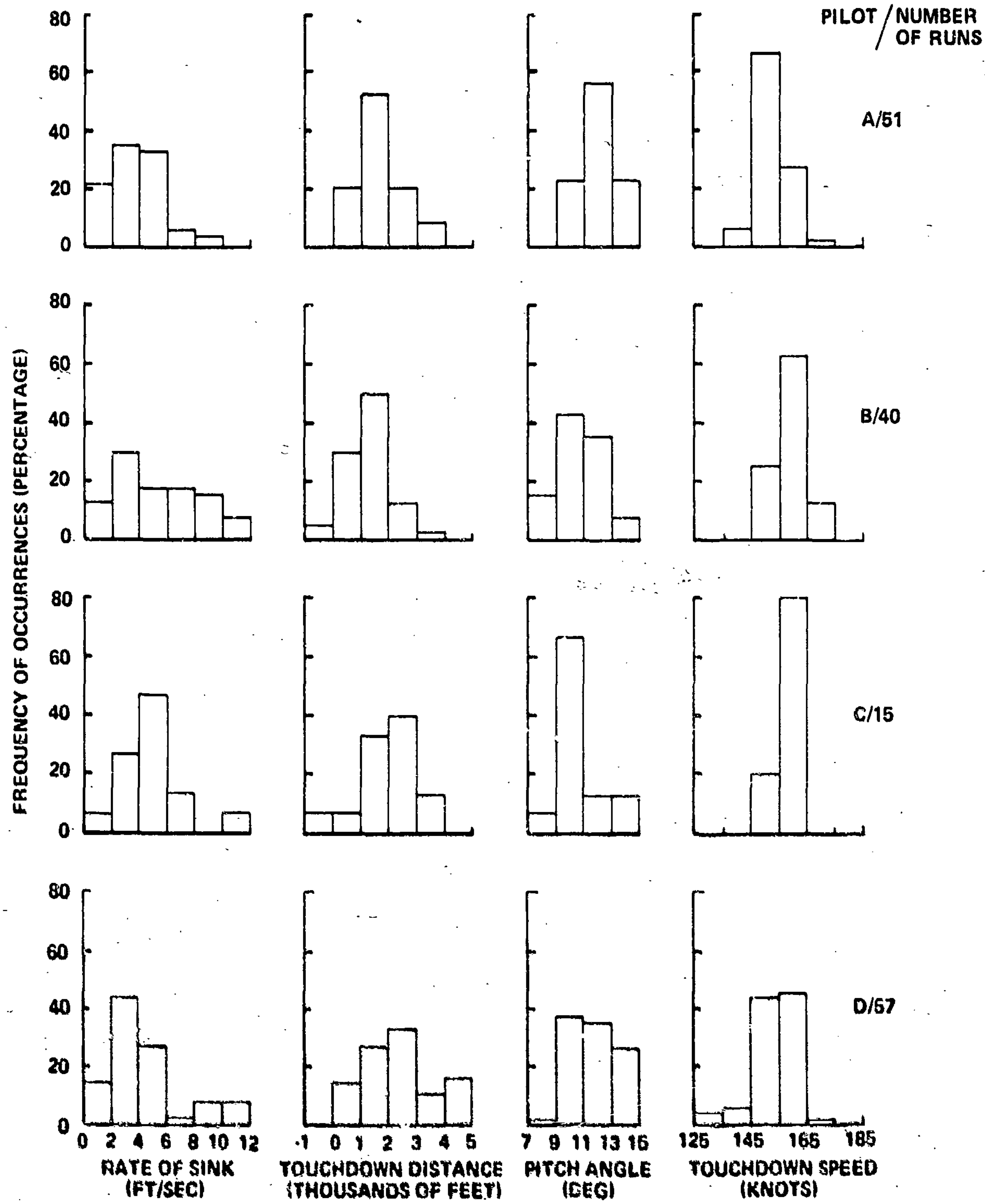


Figure 14 TOUCHDOWN PARAMETERS ACHIEVED BY INDIVIDUAL PILOTS FOR ALL CONFIGURATIONS

4.3 EXAMINATION OF PILOT RATING DATA

4.3.1 Pilot Rating Data as a Function of Short Term Equivalent Pitch Attitude Time Constant

In Appendix II of this report, it was shown that for the statically unstable airplane configurations evaluated, the short term pitch attitude response could be characterized by a first order time constant. Examination of pilot comments indicates that the pitch attitude control problems were related to the sluggishness of the pitch response to elevator. The factors which determine the initial "sluggishness" of attitude response are pitch control sensitivity, elevator control gearing, and the short term attitude characteristic of the airplane. For the statically unstable configurations evaluated in this program, only the short term attitude characteristics were varied. As used in this discussion, the short term attitude characteristic response in pitch attitude is described by the equivalent short term attitude time constant, ($1/T_{2_\theta}$ for stable short term attitude response and T_{2_θ} for unstable short term attitude response). Table VI summarizes the pilot ratings obtained in the in-flight investigation as a function of the measured equivalent short term pitch attitude time constant.

Figures 15 through 17 present pilot rating data for the primary evaluation pilots (A, B, and D) as a function of the short term attitude response time constant. Examination of these figures indicates that a trend with the level of stability of the short term attitude response is apparent for Pilots A and D. This trend is not readily apparent from the ratings of Pilot B. There can be several factors that could influence this trend. Previously, the influence of "learning curve" phenomenon was discussed in Section 4.1. Another possible significant factor is the influence of the atmospheric environment (e.g., turbulence). The influence of these factors on pilot rating is examined in the next section.

4.3.2 Influence of Turbulence on Pilot Ratings

As described in Section III of this volume, the evaluation task included examination of the airplane in turbulence. In an attempt to enable each evaluation of a configuration to be performed at a prescribed level of turbulence intensity, a special electronic circuit combining "canned" turbulence and measured turbulence was used and is described in Volume II, Section IV. The actual turbulence environment (measured plus "canned") for each evaluation was examined at the completion of the in-flight program and is tabulated in Section IX, Volume II. The actual data indicates a large variability in the turbulence intensity for the same configuration evaluated on different flights by the various pilots. Gust rms values were calculated from the time histories of the recorded turbulence environment for each of the approaches performed during the evaluation of a given configuration (Volume II). The maximum value of the total velocity gust rms ($\sigma_{V_{g_{MAX}}}$) for the different approaches was considered to be a reasonable index of the actual turbulence environment on a particular evaluation. Figure 18 presents

TABLE VI

PILOT RATING AS A FUNCTION OF SHORT TERM EQUIVALENT PITCH ATTITUDE TIME CONSTANT

Configuration	$\frac{1}{T_{1_\theta}}$	$\frac{1}{T_{2_\theta}}$	Pilot Rating			
			A	B	C	D
2	.278		4D	7;10(5;8)	-	6-7
3	.167		6-7D	6	9;10F	5;6D
4	0		5C	5;7D	-	7-8E
5		.385	10E	-	10;10F	7D(10F)
6	.111		5C(4.5C)	5;10(6E)	6;8D	8C(6D)
7		.061	6E	7;8C	6D	9F(7D)
8	0		5A	7;8D	-	5C
9		.164	6.5D	6	-	7(5.5C)
10	.167		5D	5;9C	-	7D
11	0		5D(6B)	-	-	6D
12		.385	10F	6-7;10D	-	-
14	.400		4C	-	-	6D
15	.068		6B	-	5C	7.5D
16		.385	10E	-	-	10F
17	.455		-	5;8C	-	6D
18	0		6D	7;10	-	-
19		.500	-	-	-	10F

NOTE: The equivalent pitch time constant was measured from attitude response to elevator (Appendix II)

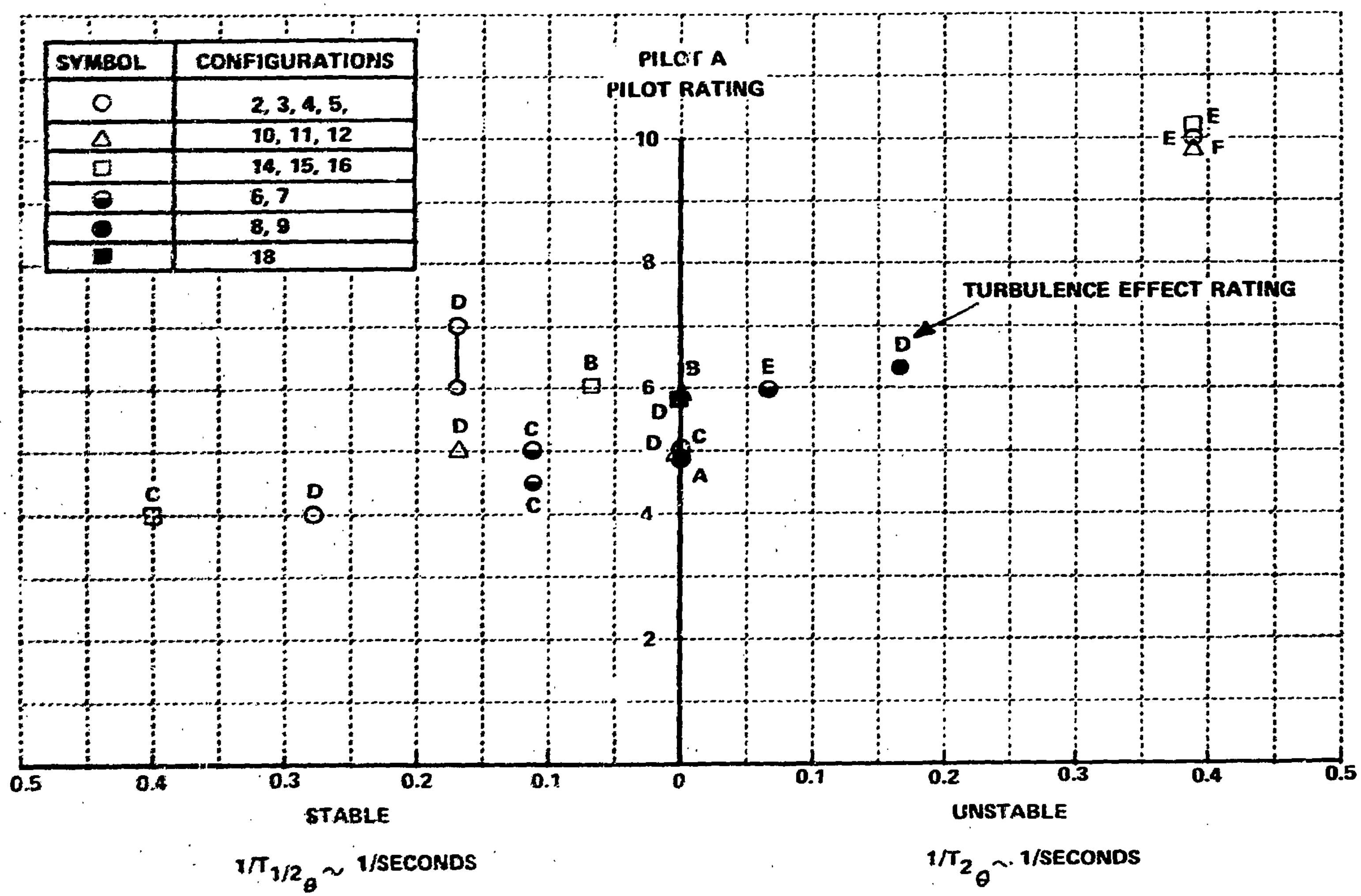


Figure 15 PILOT RATING VS EQUIVALENT SHORT TERM ATTITUDE TIME CONSTANT (PILOT A)

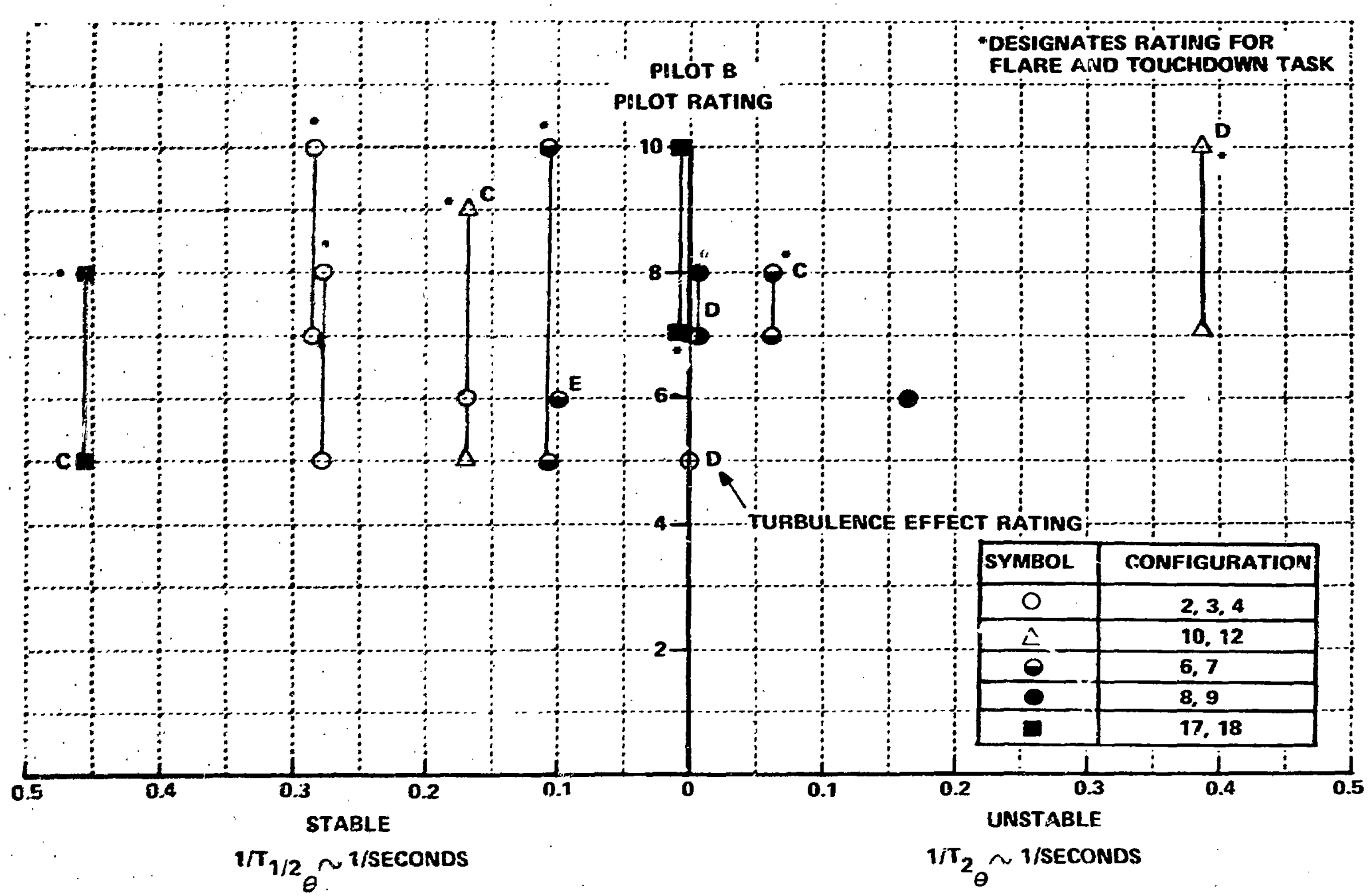


Figure 16 PILOT RATING VS EQUIVALENT SHORT TERM ATTITUDE TIME CONSTANT (PILOT B)

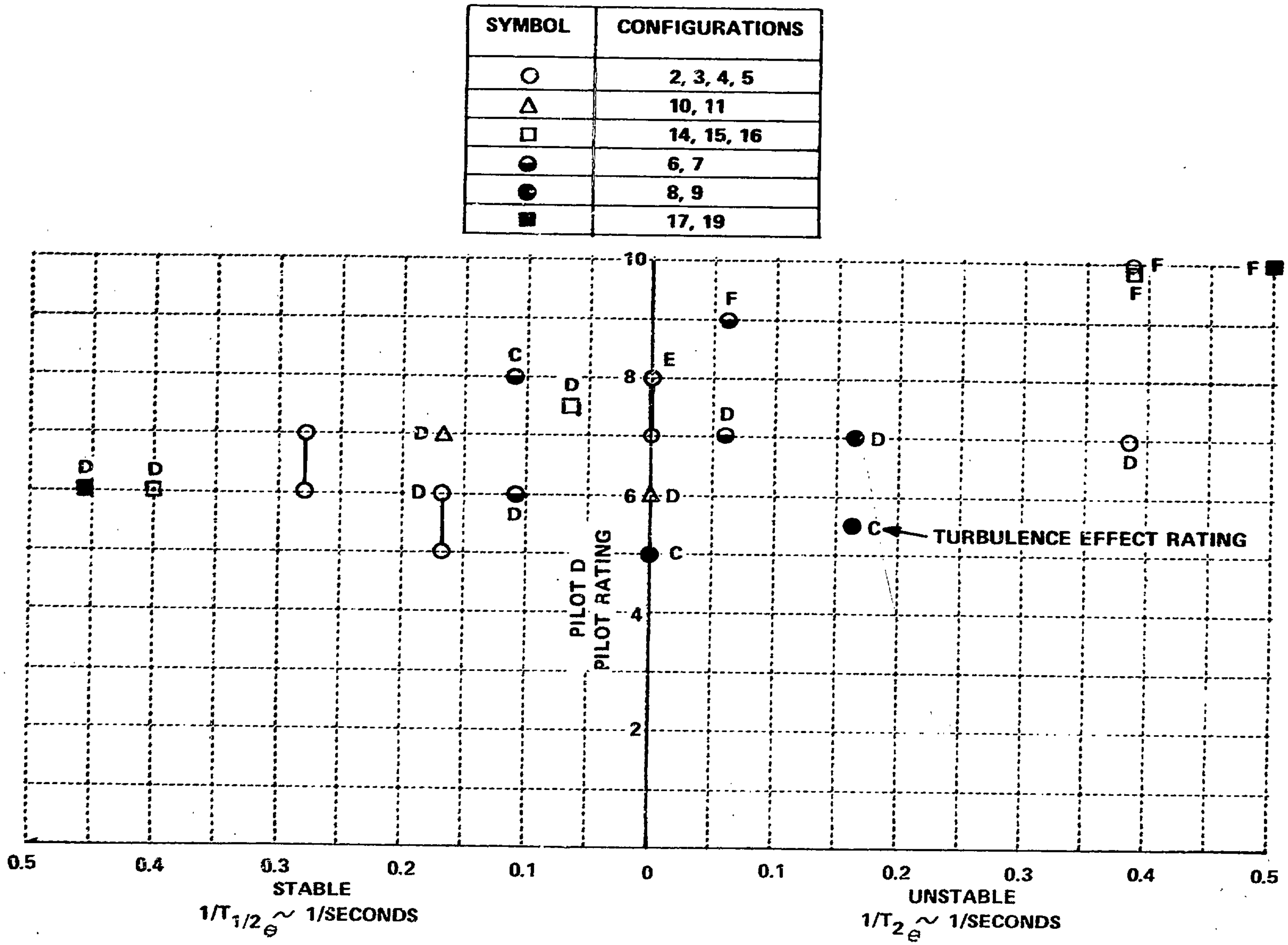


Figure 17 PILOT RATING VS EQUIVALENT SHORT TERM ATTITUDE TIME CONSTANT (PILOT D)

the pilot ratings and the turbulence effect rating for each configuration as a function of the $\sigma_{v_{g\,MAX}}$. For each configuration a trend line indicating turbulence influence on pilot rating is presented. The trend effect with turbulence was weighted by the influence of the "learning curve" (e.g., added emphasis in the determination of the trend lines was placed on repeat evaluations). From these trend lines a compensated pilot rating was determined for all configurations at two values of $\sigma_{v_{g\,MAX}}$. A value selected to indicate moderate turbulence was 3.0 feet per second, while a light level of turbulence is represented by $\sigma_{v_{g\,MAX}} = 1.5$ feet per second. In general these values tend to agree with the pilot commentary on the level of turbulence. Figures 19 and 20 present the compensated pilot rating obtained from these trend lines as a function of the airplane parameters varied in this program for the statically unstable configurations.

4.3.3 Examination of the Effects of the Stability Derivative Variations on the Compensated Pilot Ratings

This section will describe the trends in pilot rating as a function of the specific stability derivatives varied in this program based on the data presented in Figures 19 and 20. The specific items presented are as follows: (1) the influence of C_{m_α} on pilot rating, (2) the influence of backsidedness (reduction of C_{D_α}) on pilot rating, (3) the influence of pitch damping ($C_{m_q} + C_{m_{\dot{\alpha}}}$) on pilot rating, (4) influence of nonlinear C_{m_α} effects on pilot rating.

(1) Pilot rating appears to be relatively insensitive to variations in C_{m_α} until the short term attitude response becomes unstable. As C_{m_α} is made more unstable from the value which yields $1/T_{2_\theta} = 0$, the pilot rating significantly degrades for the moderate level of turbulence. For relatively light turbulence a higher value of instability could be obtained before the pilot rating indicates a significant degradation.

(2) In general, pilot rating improved slightly when the configuration was placed in the bucket of the power-required curve at the approach velocity. This tendency is more apparent for the moderate level of turbulence than for the light turbulence level.

(3) When pitch damping was increased, at constant values of the time to double amplitude determined from the unstable aperiodic root of the longitudinal characteristic equation, a tendency for pilot rating to degrade is noted. However, if C_{m_α} were not varied with ($C_{m_q} + C_{m_{\dot{\alpha}}}$) to maintain a constant time to double amplitude of the unstable root, then an improvement in pilot rating is indicated since the time to double amplitude in this situation would be increased.

(4) For the values of nonlinearity in the pitching moment as a function of angle of attack investigated in this program, there appears to be no influence on pilot rating, although the nonlinearity may require some additional pilot compensation to prevent the approach velocity from getting too slow.

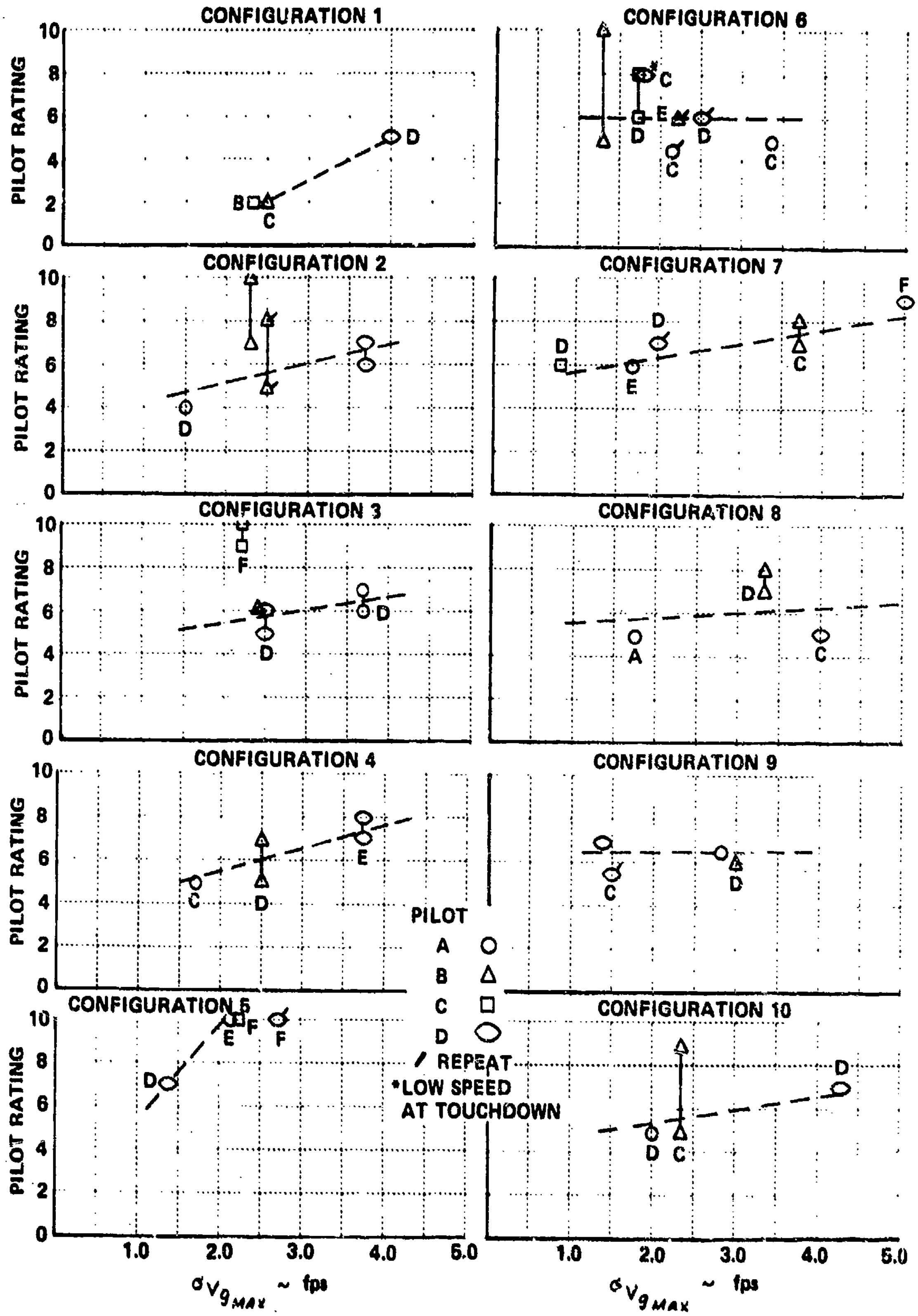


Figure 18 INFLUENCE OF TURBULENCE ON PILOT RATING

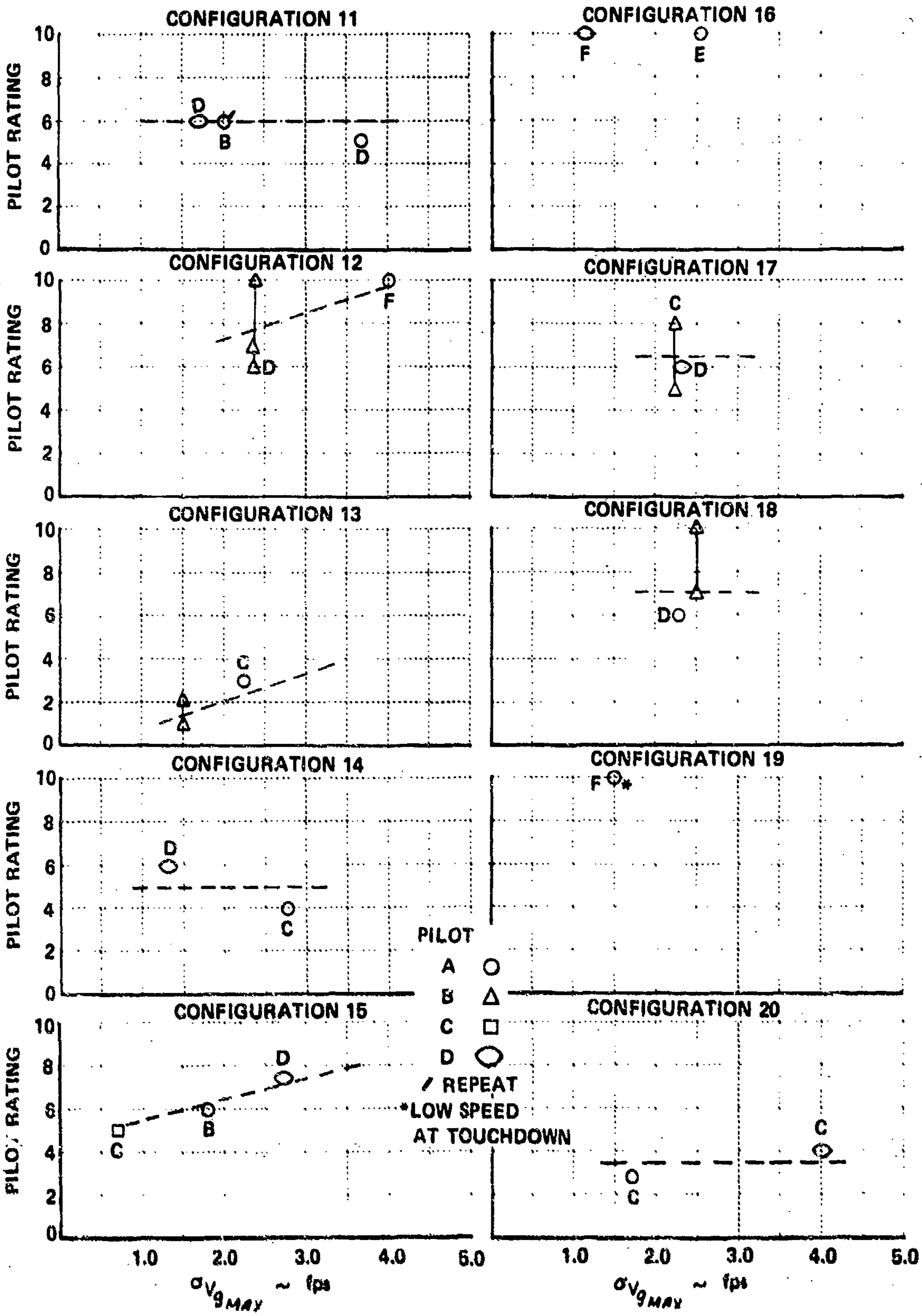


Figure 18 (Cont.) INFLUENCE OF TURBULENCE ON PILOT RATING

SYMBOL	CONFIGURATIONS
○	2, 3, 4, 5
△	10, 11, 12
□	14, 15, 16
◒	6, 7
●	8, 9
■	17, 18, 19

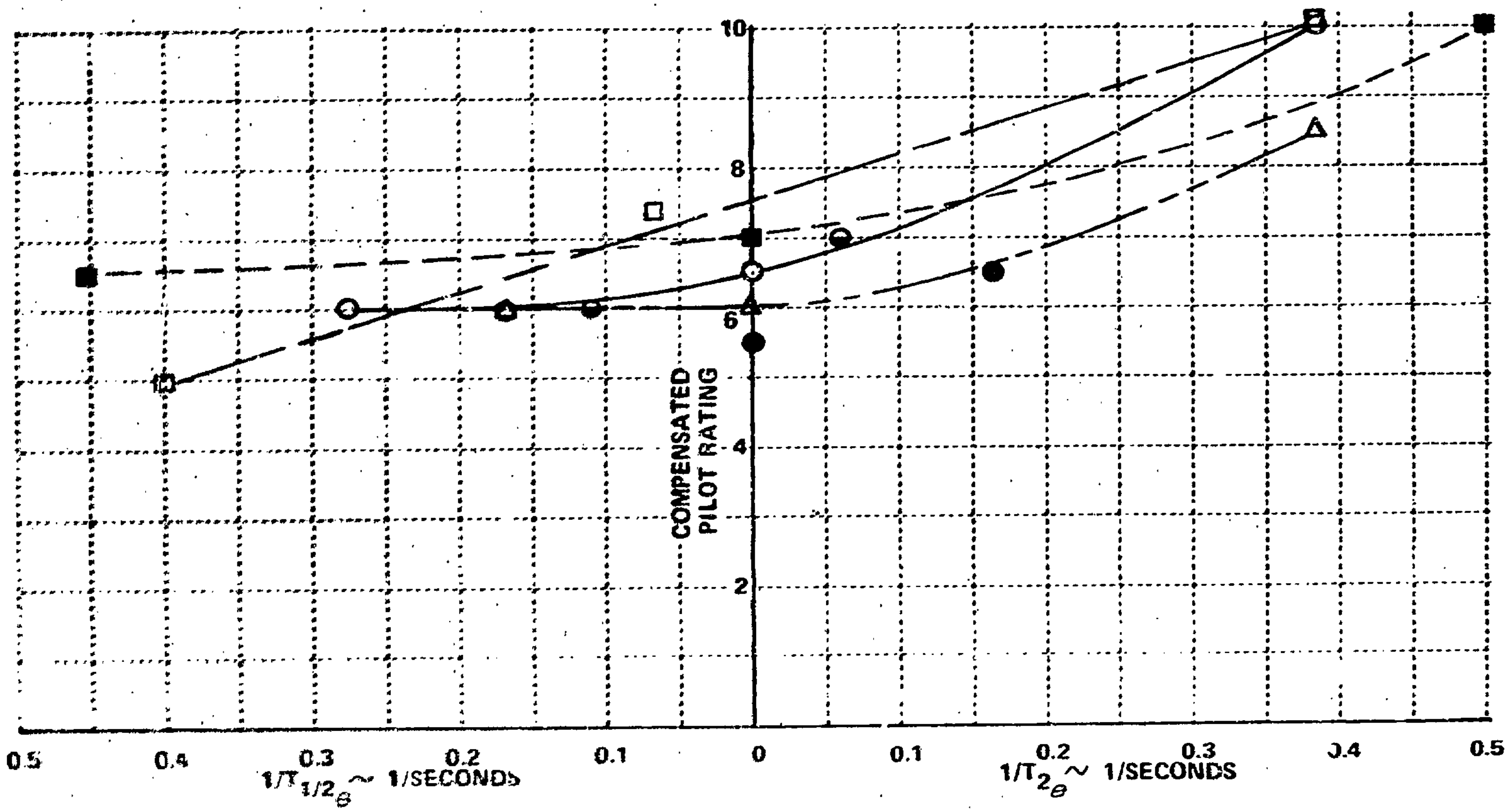


Figure 19 COMPENSATED PILOT RATING VS EQUIVALENT ATTITUDE TIME CONSTANT

($\sigma_{{\alpha_g}_{max}}$ = 3.0 FEET/SECOND)

SYMBOL	CONFIGURATIONS
○	2, 3, 4, 5
△	10, 11, 12
□	14, 15, 16
⊖	6, 7
●	8, 9
■	17, 18, 19

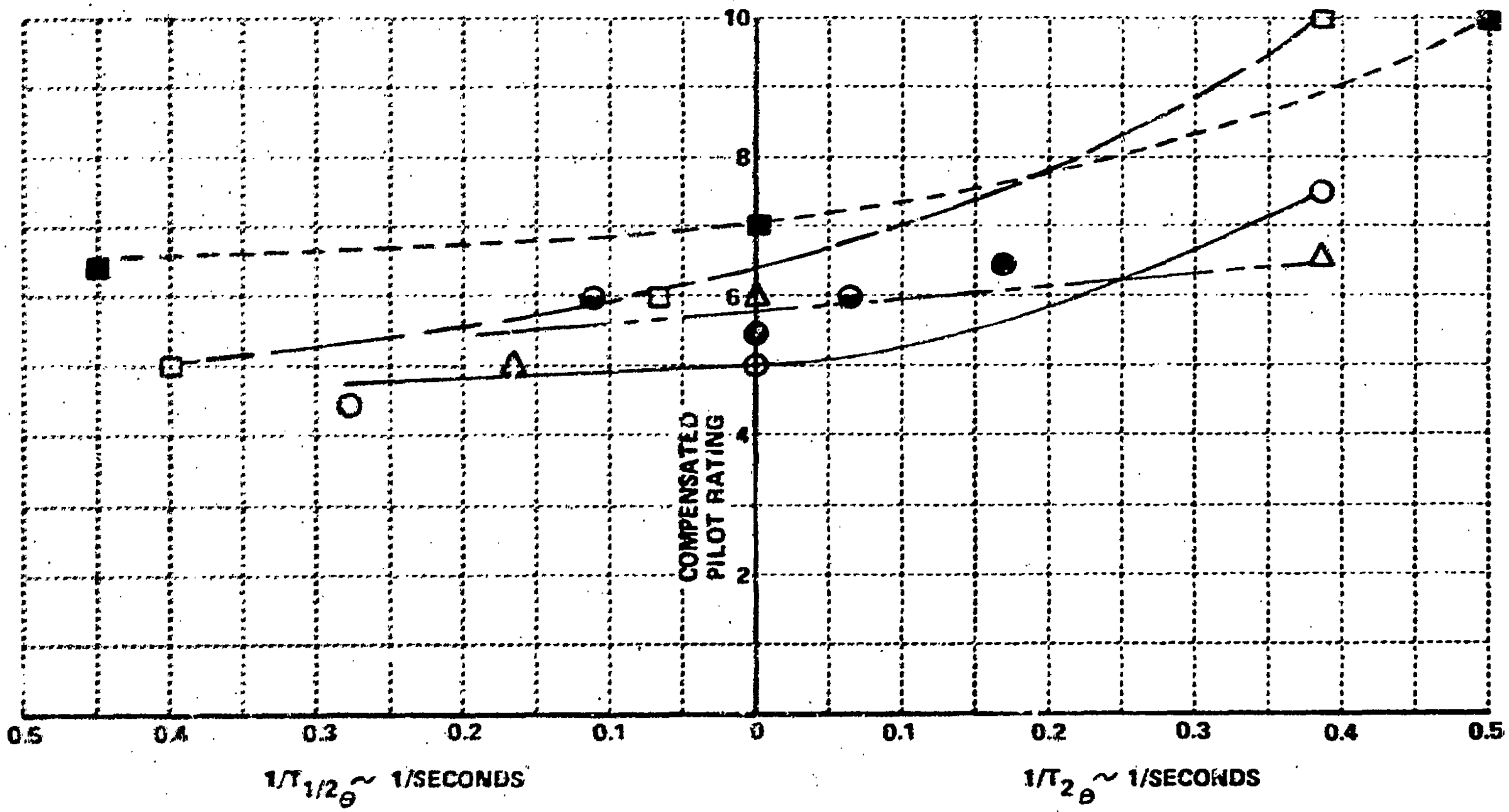


Figure 20 COMPENSATED PILOT RATING VS EQUIVALENT ATTITUDE TIME CONSTANT ($\sigma_{v_{g_{MAX}}}$ = 1.5 FEET/SECOND)

4.4 PILOT RATING CORRELATION WITH THE TIME TO DOUBLE AMPLITUDE DETERMINED FROM THE LONGITUDINAL UNSTABLE CHARACTERISTIC ROOT LOCATION

In the previous paragraphs of this section the influence of the parameters varied in this program on pilot rating was analyzed in terms of a measure of the sluggishness of the pitch attitude response. Reference 13 reports the results of experiments investigating the influence of time to double amplitude on pilot acceptability of minimum longitudinal stability for the landing approach task. The time to double amplitude used in Reference 13 was determined from the location of the unstable aperiodic root of the linearized three-degree-of-freedom longitudinal characteristic equation. This reference recommends a criterion of six seconds time to double amplitude (T_2). This recommendation was based upon a safety margin with respect to the data presented in Reference 13. The data presented is a summation of pilot ratings in terms of a mean pilot rating obtained from various experiments on fixed-base simulators, moving-base simulators and variable stability aircraft. Although the author of Reference 13 presents the pilot rating data as obtained from the Cooper Scale, examination of Reference 14 indicates the pilot rating data is actually based on the interim Cooper-Harper rating scale. The numerical pilot ratings of the interim Cooper-Harper scale are identical to the pilot rating scale used in this in-flight investigation. Table VII presents the compensated pilot ratings obtained in this investigation as a function of time to double amplitude based on the linearized characteristic equation and measurement of the angle-of-attack time history to an elevator step.

Figures 21 and 22 present the results of the experiment conducted on the TIFS airplane for mini 'ongitudinal stability in terms of the time to double amplitude characte by the unstable aperiodic root determined from a linearization of the con..gu..tions evaluated. The linearized transfer functions for the 20 configurations evaluated are presented in Appendix I. The time to double amplitude is presented in Table V of this section. On Figures 21 and 22, the compensated pilot ratings for the various parameters varied in the experiment are presented. The effects of these parameters have been discussed in Section 4.3.3. In addition, a curve representing the mean pilot rating as a function of T_2 is illustrated. Figure 23 presents a comparison of the results of this investigation into minimum longitudinal stability for a large delta-wing transport with the results presented in Reference 13. From this comparison a similar trend in pilot rating is illustrated as a function of time to double amplitude. The data of both programs indicate a lack of sensitivity of pilot rating with time to double amplitude when T_2 is greater than 6 seconds. The data obtained in this program shows a greater sensitivity of pilot rating with T_2 below 6 seconds, however, for $\sigma_{v_{g_{WAT}}}$ = 1.5 second, excellent correlation is obtained between the results of the two programs for the values of T_2 of primary interest. The minimum acceptable boundary (Cooper-Harper pilot rating = 6.5) occurs at T_2 = 2.5 seconds for both the data of Reference 13 and the light turbulence data of this investigation. This figure also illustrates that the minimum acceptable boundary (Cooper-Harper pilot rating = 6.5) occurs at a value of T_2 = 4.25 seconds for the moderate turbulence intensity data obtained in this research program.

TABLE VII

COMPENSATED PILOT RATING VS. TIME TO DOUBLE AMPLITUDE

Configuration	Linearized characteristic root location	Measured from nose-up elevator input	Measured from nose-down elevator input	Compensated Pilot Rating	
	$1/T_2$ ~ sec^{-1}	$1/T_{2_\alpha}$ ~ sec^{-1}	$1/T_{2_\alpha}$ ~ sec^{-1}	σ = 3.0 ft/sec	σ = 1.5 ft/sec
2	.017	.139	.000	6	4.5
3	.123	.161	.100	6	5
4	.240	.242	.200	6.5	5
5	.500	.500	.500	10	7.5
6	.123	.250	.000	6	6
7	.240	.323	.119	7	6
8 *	.123	.323	.000	6	5.5
9 *	.240	.370	.000	6.5	6.5
10	.103	.141	.080	6	5.0
11	.217	.217	.175	6	6.0
12	.476	.476	.476	8.5	6.5
14	.122	.170	.110	5	5
15	.240	.238	.210	7.5	6
16	.502	.500	.500	10	10
17	.122	.208	.060	6.5	6.5
18	.240	.294	.140	7	7
19	.502	.555	.420	10	10

* Configurations 8 and 9 time histories of angle of attack to elevator input indicate a significant stabilizing trend with time for a nose-down command.

SYMBOL	CONFIGURATIONS
○	2, 3, 4, 5
△	10, 11, 12
□	14, 15, 16
◒	6, 7
●	8, 9
■	17, 18, 19

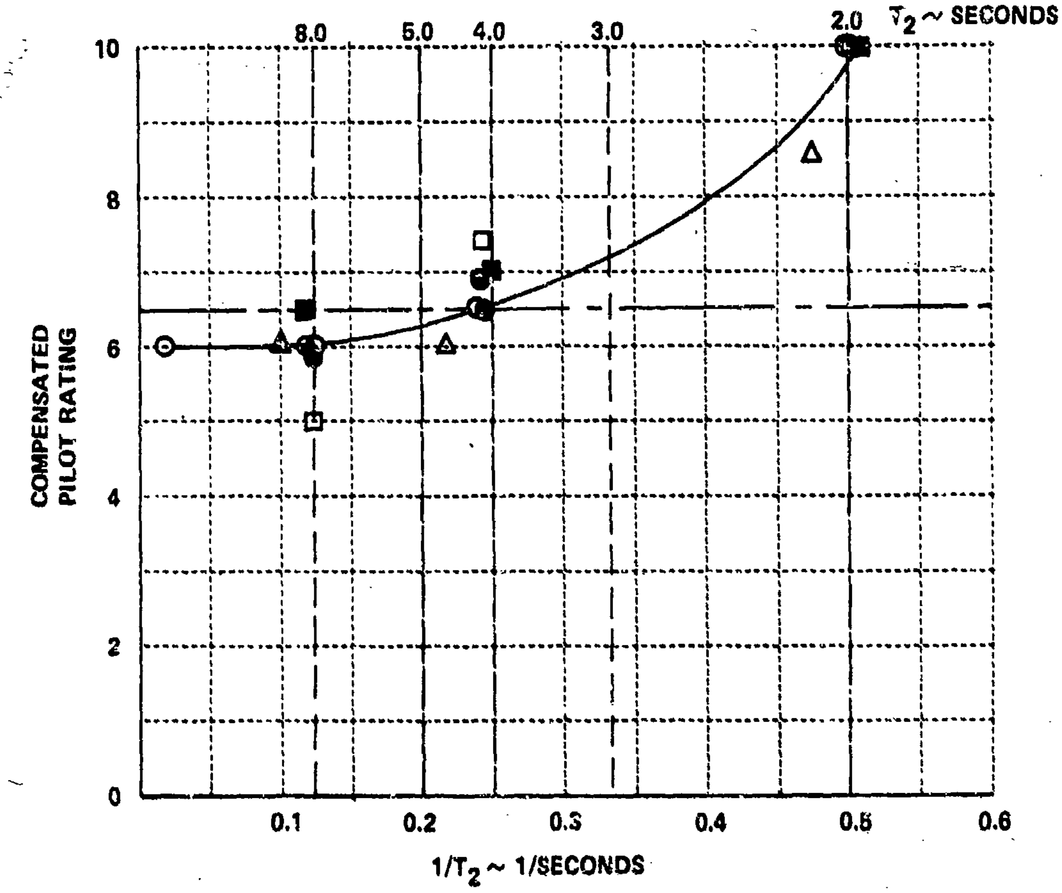


Figure 21 COMPENSATED PILOT RATING VS TIME TO DOUBLE AMPLITUDE (UNSTABLE ROOT LOCATION) ($\sigma_{V_{g_{MAX}}}$ = 3.0 FEET/SECOND)

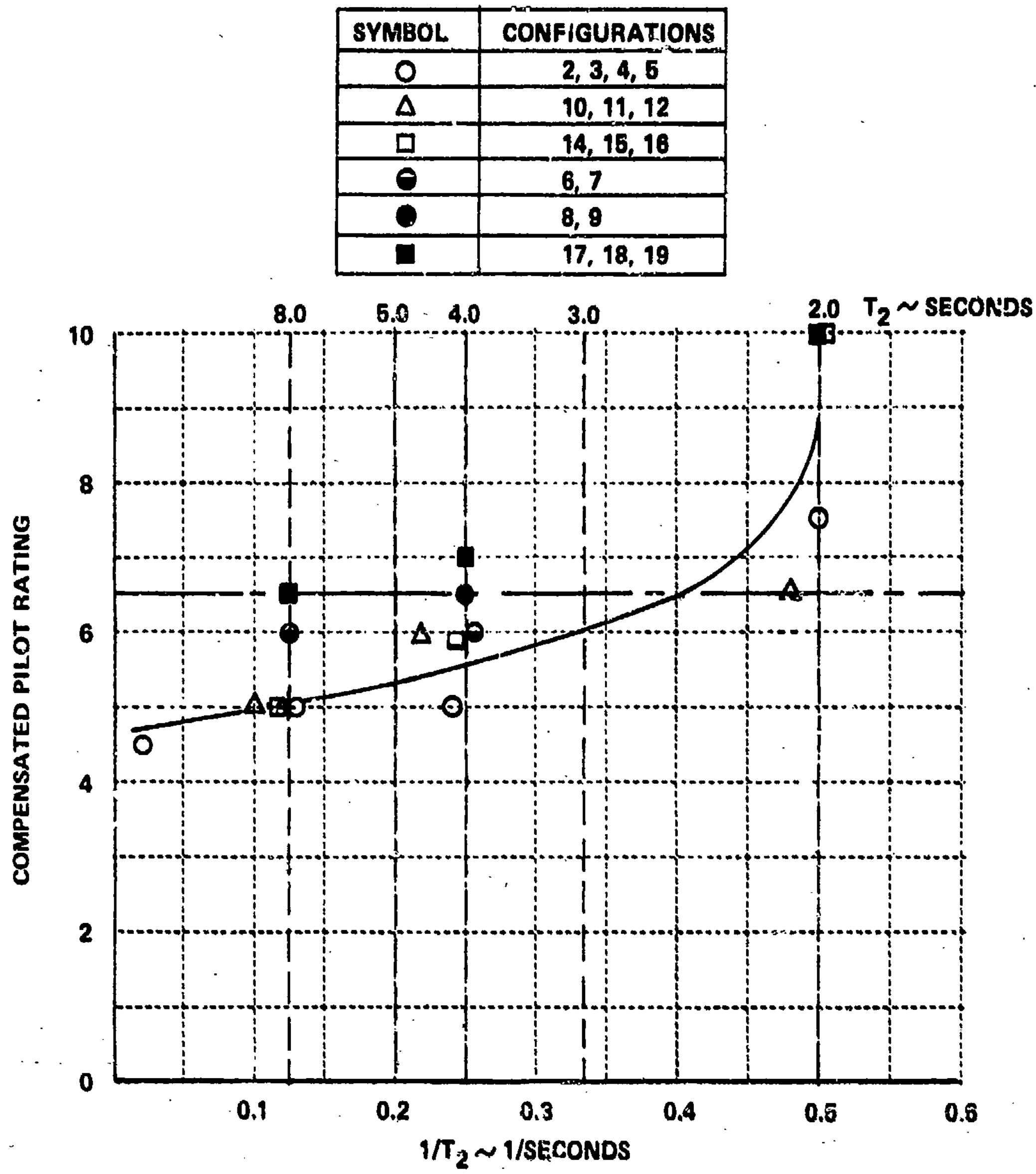


Figure 22 COMPENSATED PILOT RATING VS TIME TO DOUBLE AMPLITUDE (UNSTABLE ROOT LOCATION) ($\sigma_{V_{g_{MAX}}}$ = 1.5 FEET/SECOND)

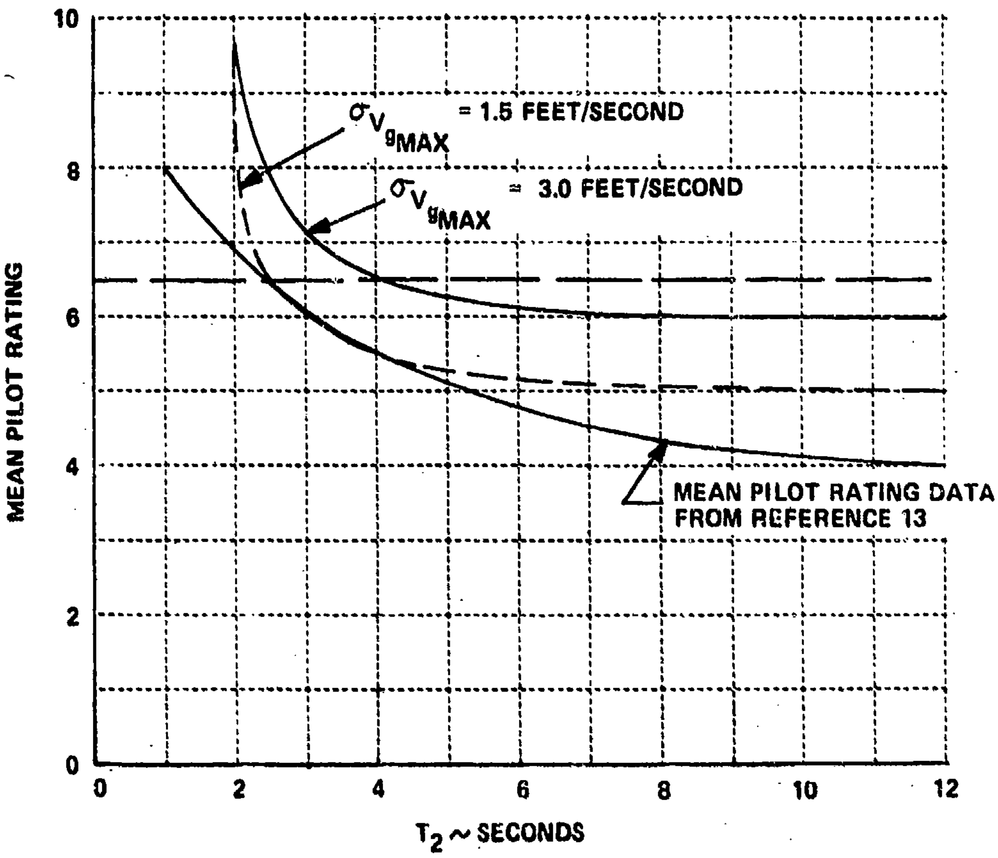


Figure 23 COMPARISON OF MEAN PILOT RATING WITH DATA IN REFERENCE 13

4.4.1 Pilot Rating Correlation with the Time to Double Amplitude Measured from Angle of Attack Time History to Elevator Input

Table VII includes the time to double amplitude measured from angle of attack response to elevator input (T_{2_α}). As previously presented in Section II of this volume, the measured value of T_{2_α} is dependent upon the direction of control input. The trend in compensated pilot rating with T_{2_α} measured from control inputs in either direction is similar to the trend obtained from correlation with T_2. However for minimum acceptable value of time to double that might be used for a criterion can vary significantly. For example, examination of the data in Table V ($\sigma_{v_{g_{MAX}}}$ = 3.0 ft/sec) indicates that for Configurations 2, 3, 4 and 5, the minimum acceptable boundary (Cooper-Harper pilot rating - 6.5) occurs at a value of T_{2_α} = 4.13 seconds for a nose-up elevator input, and a value of T_{2_α} = 5.0 seconds for a nose-down elevator input. The error in the values of T_{2_α} becomes larger when pitching moment nonlinearities with angle of attack are present (e.g., Configuration 9). Thus, although the time to double amplitude measured from angle of attack response to elevator could be used as a criterion for minimum acceptable longitudinal stability, a flight compliance test should consider the direction of control input.

4.5 SUMMARY OF PILOT COMMENTS

Configuration 1	Pilot B	Flight 182-2
Pilot Rating/Turbulence Effect Rating		2C

The airplane was a very simple one because it was statically stable but it wasn't obvious whether the airplane was in the bucket of the power-required curve. The airplane felt a little too springy. More pitch rate damping would have been desirable.

Configuration 1	Pilot C	Flight 199-2
Pilot Rating/Turbulence Effect Rating		2B

The airplane appeared stable and was relatively easy to trim. The induced drag was quite apparent. The airplane appeared to lose airspeed quite rapidly with small increases of angle of attack or load factor. Adjustments were made to the glide slope with throttle, and airspeed was maintained with pitch attitude. The sink rate prior to touchdown seemed to break itself with very little flare. The required input was an increase in stick force to maintain the attitude.

Configuration 1	Pilot D	Flight 185-1
Pilot Rating/Turbulence Effect Rating		5D

Difficult to control flight path without excessive airspeed excursions. Short period response predictable and fairly good, control of pitch attitude pretty good. Throttle used in conjunction with pitch angle to control altitude and rate of descent. Considerable pilot compensation required to control flight path in the IFR approach. Turbulence induced flight path errors that were difficult to correct.

Configuration 2	Pilot A	Flight 167-2
Pilot Rating/Turbulence Effect Rating		4D

The pitch had a slow and light instability. The increased workload wasn't very much because the divergence was relatively slow. Airspeed was more of a problem than the pitch control. The turbulence was causing as much or more of a problem than the divergence. The backside of the power curve was causing the problem more than the pitch.

Configuration 2	Pilot B	Flight 181-1 (184-3)
Pilot Rating/Turbulence Effect Rating		7;10 (5;8)

The airplane wasn't really trimmable and it had no divergence. Maneuvering was reasonably precise. Airspeed caused the greatest problem on the glide slope. The flare and touchdown was bad because of the ground effect, the turbulence, and the downwind landing conditions. Also, the elevator control power was too little in the flare.

Configuration 2	Pilot D	Flight 168-2
Pilot Rating/Turbulence Effect Rating		6-7

Pitch response sluggish, had to fly tight on pitch attitude. Airspeed control adequate, requires a lot of throttle to keep on airspeed in turns. Airplane a "handful" to control in turbulence.

Configuration 3	Pilot A	Flight 166-1
Pilot Rating/Turbulence Effect Rating		6-7D

The rate of divergence was low to moderate. A normal input was used to start the nose pitching and then a reversal to stop it. The high induced drag was evident because of the fairly high decay of airspeed when maneuvering. Airspeed control was a problem during some of the approaches. The performance workload in the flare and touchdown was too high because of the phugoid.

Configuration 3	Pilot B	Flight 184-1
Pilot Rating/Turbulence Effect Rating		6

The airplane was fairly divergent and wanted to pitch up a little more at higher angles of attack than at the trim speed of 160 knots. The divergence could really be felt when maneuvering. The sluggishness could be compensated for by putting large inputs in and taking them out again. This pumping effect helped the performance in the flare and touchdown.

Configuration 3	Pilot C	Flight 201-2
Pilot Rating/Turbulence Effect Rating		9;10F

The airplane diverged very easily and quickly. Attitude control became quite difficult because of the moderate turbulence. Airspeed control was quite difficult because of the high induced drag. Control technique and workload in the flare was very difficult. The primary reason for the rating was because the airplane diverged very rapidly and required continuous and very rapid pulses to hold the attitude. The workload had almost reached the point of complete saturation.

Configuration 3	Pilot D	Flight 203-2
Pilot Rating/Turbulence Effect Rating		5;6D

Sluggish pitch response, particularly objectionable during flare and touchdown. Configuration is a little unstable in pitch and appears to be bottom side except at low speeds. Airspeed control requires some attention but does not seem to depart, reduces pilot workload.

Configuration 4	Pilot A	Flight 198-1
Pilot Rating/Turbulence Effect Rating		5C

The divergence was light to moderate. Off-trim airspeed, the reversal of the stick force was an objectionable behavior. Airspeed control required a fair amount of attention. The instability caused a minor increase in workload. A doublet was used to control the pitch instability.

Configuration 4	Pilot B	Flight 179-3
Pilot Rating/Turbulence Effect Rating		5;7D

The airplane has a divergence but it didn't seem to be too rapid since pitch attitude was reasonably managed. The pitch angular acceleration was too small to fly a very tight loop. There was an unstable drag speed relationship. The landings were reasonable since there was some control through the approaches and landings.

Configuration 4	Pilot D	Flight 186-1
Pilot Rating/Turbulence Effect Rating		8E

Controllability in flare requires a lot of lead to control flight path. Airplane pitch instability is noticeable, however, good performance is achievable IFR if tight on attitude indicator. Must control airspeed errors promptly. Tradeoff control of touchdown point for control of sink rate at touchdown. Turbulence definitely degrades configuration.

Configuration 5	Pilot A	Flight 192-1
Pilot Rating/Turbulence Effect	Rating	10E

The airplane was constantly attempting to get away in pitch. There was a fairly high stick force gradient in the unstable side but it made trimming easier than some of the other configurations. The airspeed decayed very fast in a turn because the induced drag was quite high. Pitch control was primary in this configuration.

Configuration 5	Pilot C	Flight 201-3
Pilot Rating/Turbulence Effect	Rating	10;10F

Maneuvering about level flight required very rapid and very large pulses to maintain any satisfactory degree of attitude control. The drag increase with the g's was very large. Airspeed control was a little difficult partly because of the intense concentration required for attitude control. Flare and touchdown was literally an impossible task 99% of the time.

Configuration 5	Pilot D	Flight 187-1 (203-3)
Pilot Rating/Turbulence Effect	Rating	7D (10F)

The following comments apply to a flight with good visibility and very little turbulence. Workload high. Requires tight attitude loop IFR and a lot of elevator lead to control pitch attitude at touchdown. Poor control of touchdown point. Aircraft appears to be bottom of the bucket, control of airspeed is adequate but demanding.

For an approach in increased turbulence, the following comments apply. Airplane very demanding in terms of workload. Requires a lot of manipulation of elevator to keep attitude bounded and a lot of throttle manipulation to bound airspeed. Required grossly abnormal elevator for flare and touchdown control.

Configuration 6	Pilot A	Flight 165-1 (170-3)
Pilot Rating/Turbulence Effect	Rating	5C

The airplane was unstable in a different way because it hesitated before "creeping" on-off and it was insidious. Turbulence was causing as much a problem as the instability. Keeping the airspeed low was troublesome. The elevator had to be worked up and down like a bilge pump. The workload in the pitch task was increased but not much. In the flare there was a lag in the effectiveness of the elevator.

Configuration 6 Pilot B Flight 178-1 (182-1)

Pilot Rating/Turbulence Effect Rating 5;10

The airplane seemed to have a mild divergence. The approach required considerable attention but the amount wasn't too much greater than a normal approach in a more conventional airplane in rough air. The back side of the power was quite evident. Airspeed and attitude management were constantly distracting me. The major problem was in the flare and touchdown. The approaches were reasonable but the flare and touchdowns were not and would have resulted in crashes.

The divergence was very small but the most objectionable feature was speed power management which was unstable. There wasn't any trouble with the ground effect moment and there was a good feeling for the flare and touchdown.

Configuration 6 Pilot C Flight 201-1

Pilot Rating/Turbulence Effect Rating 6;8D

The airplane appeared quite unstable and once a pitch rate developed, it diverged fairly rapidly. Considerable attention was required for pitch control. Airspeed control was a little bit difficult in that, if the nose was lowered slightly, the airspeed built up an extra 10 knots in a very short period of time. The workload in the flare was quite high. The only satisfactory way to land the airplane was to lock in the attitude and change nothing during the last 100 feet.

Configuration 6 Pilot D Flight 171-1 (202-1)

Pilot Rating/Turbulence Effect Rating 8C

Difficult to control pitch attitude in flare and touchdown. Pitch up tendency when slow, requires attention to control airspeed. Airplane appears in bucket for small speed changes. Required tight loop on climb rate in turns; attitude control is not enough. Requires tight pitch control on glide slope, which interferes with control of heading, etc. Sluggish pitch response especially in flare and touchdown is objectionable.

Configuration 7 Pilot A Flight 167-1

Pilot Rating/Turbulence Effect Rating 6E

The divergence was moderately fast. Maneuvering about level flight required a moderate amount of increased workload due to the pitch instability. The airplane had a fairly high induced drag. Airspeed was a problem and it would get off more on the low side than the high. However, on the glide path, the problem was keeping the airspeed from increasing. On this flight, the technique of just breaking the sink and letting the airplane fly into the ground was used for the first time.

Configuration 7 Pilot B Flight 184-2

Pilot Rating/Turbulence Effect Rating 7;8C

The airplane had very little divergence about the trim airspeed but it tended to diverge more at the higher angles of attack. Maneuvering stability was negative. Workload in the flare was a problem. Adequate elevator power to produce a flare and overcome the ground effect was not available. Speed stability was bad and speed management on the backside was a problem.

Configuration 7 Pilot C Flight 200-1

Pilot Rating/Turbulence Effect Rating 6D

The airplane appeared to be mildly divergent. Workload became noticeably heavy because of the increased scan rate required to prevent the attitude divergence. Airspeed control was moderately difficult. On the slow side the airspeed tended to bleed off fairly rapidly because of the increased induced drag. The control technique for power management was holding attitude to maintain airspeed.

Configuration 7 Pilot D Flight 168-1 (203-1)

Pilot Rating/Turbulence Effect Rating 9F (7D)

High workload configuration IFR requires constant cross check on airspeed and pitch attitude, particularly to stay on glide slope. Must anticipate glide slope interception. Substantial manipulation of elevator required to control pitch attitude in flare, with frequent throttle corrections for control of speed. Pitch has tendency to diverge, difficult to trim. Pitch control is poor due to sluggish response, some concern about controllability in flare and touchdown.

Configuration 8 Pilot A Flight 191-1

Pilot Rating/Turbulence Effect Rating 5A

The airplane was a little bit unstable. A little more workload was required because of the low divergence rate. A little airspeed was lost when turning but airspeed was no big problem. Pitch control was probably most degraded because of the tendency to wander in pitch.

Configuration 8 Pilot B Flight 180-1

Pilot Rating/Turbulence Effect Rating 7;8D

Too much attention was required in both pitch attitude and speed management; primarily speed and power management were difficult because of the backside kind of operation. The airplane didn't respond quickly enough but if the control power were higher it might have been easier to manage. The basic pitch response was poor and was the overriding consideration, particularly in the flare.

Configuration 8 Pilot D Flight 186-2

Pilot Rating/Turbulence Effect Rating 5C

Airplane is sluggish in pitch, appears to be in the bucket for small speed changes. Some pitch instability but not significant. Maneuvering forces very light. Strong nose-down tendency in ground effect, which is difficult to control. Control of airspeed requires attention but is not a high workload item.

Configuration 9 Pilot A Flight 199-1

Pilot Rating/Turbulence Effect Rating 6.5D

The airplane had kind of a moderate instability. Airspeed control was a fair amount of trouble because of the induced drag. More emphasis was placed on the attitude indicator because of the pitch divergence.

Configuration 9 Pilot B Flight 183-2

Pilot Rating/Turbulence Effect Rating 6

The airplane had a slight divergence that appeared to be a little worse at higher angles of attack. At lower speeds, the divergence was a little more dangerous. The maneuvering stability seemed to be negative. Speed management was fairly simple. The instability at the higher angle of attack helped to fly the airplane through the ground effect on touchdown.

Configuration 9 Pilot D Flight 176-1 (188-1)

Pilot Rating/Turbulence Effect Rating 7 (5.5C)

Airplane is sluggish in pitch, and airspeed is slippery causing difficulties in airspeed control during IFR flight. Pitch control in flare and touchdown to control sink rate, etc. requires strong attention. Tendency to PIO during flare and touchdown.

Configuration 10 Pilot A Flight 170-2

Pilot Rating/Turbulence Effect Rating 5D

The airplane had a very slow divergence. Airspeed wasn't too big of a problem. Pitch control caused a little more work. The pitch instability caused more attention to be paid to the attitude indicator.

Configuration 10 Pilot B Flight 179-2

Pilot Rating/Turbulence Effect Rating 5;9C

The airplane was slightly divergent at a fairly slow rate and didn't seem to have any nonlinearities in the pitching moment curve. The speed divergence seemed to be negligible and so it was in the bucket. Maneuvering stability was neutral to unstable. The ground effect caused the greatest difficulty and the airplane wasn't under control below 50 feet above the ground.

Configuration 10 Pilot D Flight 172-2

Pilot Rating/Turbulence Effect Rating 7D

Difficult to correct flight path errors close to ground due to sluggish pitch response and PIO tendency. Airspeed control is good. Divergence in altitude open loop, but in maneuvers it appears as just a sluggish response. Control in flare requires tight control of pitch attitude, need to detect incipient pitch rates, and make immediate corrections to keep error small. Large corrections tend to cause trouble.

Configuration 11 Pilot A Flight 166-2 (191-2)

Pilot Rating/Turbulence Effect Rating 5D (6B)

The airspeed wasn't too much of a problem on the approaches. The airplane has a very slow divergence in pitch. Pitch attitude had to be watched a little more than normally. Holding a constant attitude in ground effect was difficult because the pitching moment at the last caused the nose to start down. The turbulence excited the instability and caused all kinds of problems.

Configuration 11 Pilot D Flight 187-2

Pilot Rating/Turbulence Effect Rating 6D

Airplane has a relatively slow divergence rate in pitch, and feels sluggish in response to corrective pitch inputs. Hard to control pitch attitude in flare and touchdown. Sluggish pitch response requires pilot to overdrive using fairly large control inputs. Airspeed control is much less a factor in pilot workload; however, control of airspeed is demanding in turns and when making altitude changes.

Configuration 12 Pilot A Flight 165-2

Pilot Rating/Turbulence Effect Rating 10F

The airplane was pretty unstable and nosedown was worse than noseup. Attitude control was the primary concern. The airspeed control wasn't a problem. Turbulence excited the instability and the doublet technique was used to stop the pitching motion. The maneuvering forces were hard to see. The stops were hit on the elevator in ground effect.

Configuration 12 Pilot B Flight 179-1

Pilot Rating/Turbulence Effect Rating 6-7;10D

The airplane was extremely sluggish and divergent. Maneuvering stability was effectively negative. Speed management was probably the best thing about the whole configuration. The biggest problem was encountered in ground effect controlling pitch attitude rates in the flare. Touchdown management was intolerable and each landing would have resulted in a crash.

Configuration 13 Pilot A Flight 198-2

Pilot Rating/Turbulence Effect Rating 3C

Attitude control was relatively easy. The stick forces in a turn were fairly substantial. The airspeed control was no problem. The trim change in ground effect was marked because the forces were so much higher than other configurations.

Configuration 13 Pilot B Flight 178-2

Pilot Rating/Turbulence Effect Rating 1-2

The airplane was stable. Maneuvering stability was reasonably high; in fact, it was quite high. The airplane had positive longitudinal stability and no PIO in the flare due to ground effect. Power management was simple.

Configuration 14 Pilot A Flight 169-1

Pilot Rating/Turbulence Effect Rating 4C

The airplane appeared to be just a little bit unstable. Attitude control was a minor problem but airspeed was a fair problem. A lot of throttle was required to recover the airspeed so it looked like high induced drag. The pitch task had minimal effect. The big workload problem was power control for airspeed.

Configuration 14 Pilot D Flight 188-2

Pilot Rating/Turbulence Effect Rating 6D

Airplane appears to be bottom-side except at low speeds. Pitch response is sluggish to control input, and appears to be slightly unstable at high speed and noticeably unstable at low speeds. Has a definite pitch-up tendency at low speeds. Tendency to get high and fast, correcting glide slope errors. Must generate lead and overdrive elevator to control flight path during flare and touchdown. Tendency to land long (float) in order to achieve a reasonable sink rate.

Configuration 15 Pilot A Flight 197-1

Pilot Rating/Turbulence Effect Rating 6B

The airplane had a moderate instability but it didn't diverge real fast. It seemed to be well damped. The nose didn't take off immediately but it built up to a fairly moderate pitch rate. Although the airspeed control was relatively easy, there was a lot of induced drag. A combination of visual and instruments for the flare and landing was used to keep the pitch attitude around 10°.

Configuration 15 Pilot C Flight 200-2

Pilot Rating/Turbulence Effect Rating 5C

The airplane tended to diverge fairly rapidly but was easier to control. Pitching rate was easier to stop when a divergence occurred. When the nose was pushed over to get on the glide slope, the airspeed increased very rapidly. The pitch divergence was much more gradual initially for the first degree or so and so it was easier to control. Control travels for minor pitch corrections were a little more than desirable for a transport aircraft.

Configuration 15 Pilot D Flight 202-2

Pilot Rating/Turbulence Effect Rating 7.5D

Airplane is objectionable, has a pitch instability, and appears to be on backside of power curve. Rather difficult to achieve trim. Pitch response is sluggish. Must monitor attitude and descent rate very closely to stay on glide slope. Considerable power management required to control airspeed. Sluggish pitch response in flare and touchdown particularly is most objectionable.

Configuration 16 Pilot A Flight 169-2

Pilot Rating/Turbulence Effect Rating 10E

The airplane has a strong instability and it was on the backside. Anything that was done even in level flight required a lot of attention to the attitude indicator. The pitch attitude required most of the increased workload but the airspeed was also causing problems. The technique of dropping below the glide slope so as not to get into a PIO in ground effect was used. Everything was degraded because most of the time was spent maintaining an attitude and trying to keep the airspeed under control.

Configuration 16 Pilot D Flight 171-2

Pilot Rating/Turbulence Effect Rating 10F

Airplane is very unstable. Very difficult to achieve trim. Tendency to PIO in attitude; airspeed and altitude control is very difficult. Requires continuous closed loop control in pitch. Workload very, very high. Airplane characteristics degrade all tasks associated with the mission.

Configuration 17	Pilot B	Flight 183-1
Pilot Rating/Turbulence Effect Rating		5;8C

The airplane was on the backside of the drag curve. Speed control was difficult and required extensive throttle manipulation and management. There was some divergence nose up but there didn't appear to be any nose down. The approach wasn't a great problem but the flare and touchdown was because of the inability to control descent rate in the flare.

Configuration 17	Pilot D	Flight 176-2
Pilot Rating/Turbulence Effect Rating		6D

Airplane appears to be nonlinear. Turn is relatively easy to achieve except that it does require tight attitude stabilization. Response is sluggish in pitch and airspeed control is difficult. Difficult to control attitude and glide path in flare unless glide slope error is small. High workload to control airplane in flare. Control of pitch attitude is easier than airspeed during approach. Difficult to detect ground effect until after attitude has started to change.

Configuration 18	Pilot A	Flight 192-2
Pilot Rating/Turbulence Effect Rating		6D

The airplane was unstable statically and aperiodic in the motion. The maneuvering forces were very light and the configuration tended to pitch up when an attempt was made to get a given g. Maintaining g in a turn was difficult.

Configuration 18	Pilot B	Flight 181-2
Pilot Rating/Turbulence Effect Rating		7;10

The airplane had a nonlinear pitching moment with the pitch up tendency becoming greater as the airspeed got slower. The unstable pitching moment as the speed went below trim was the most objectionable feature. Speed/power management was too wild. The speed control problem was very dangerous on the approach.

Configuration 19	Pilot D	Flight 176-3
Pilot Rating/Turbulence Effect Rating		10F

Airplane is quite unstable in pitch and airspeed. Very difficult to trim, almost impossible. Attitude and airspeed control is just as difficult IFR as it is visual. Task performance is very, very poor and workload very, very high. Pitch attitude control requires as tight elevator control as possible with as much lead as pilot can generate. Control of attitude in flare requires stop-to-stop column travel.

Configuration 20 Pilot A Flight 170-1

Pilot Rating/Turbulence Effect Rating 3C

The airplane was pretty easy to fly. Airspeed control wasn't any problem and the workload was minimal. The configuration was good enough that the only problem was the lateral-directional. There was a little bit of trouble in the flare due to overcontrolling and porpoising at the end of the flare.

Configuration 20 Pilot D Flight 172-1

Pilot Rating/Turbulence Effect Rating 4C

Pitch response relatively prompt and predictable. Fairly easy to trim. Flare and touchdown required large control forces and altitude response is somewhat sluggish. Airspeed control requires some attention but it not a significant problem. Rudder coordination in turns becomes objectionable due to large rudder breakout force.

SECTION V

SUMMARY AND CONCLUSIONS

An in-flight simulation and evaluation of minimum longitudinal stability for large delta-wing transports in the landing approach flight phase was conducted using the USAF Total In-Flight Simulator (TIFS). The capability of the TIFS airplane to simulate large delta-wing jet transports in landing approach conditions, including ground effect and touchdown, was clearly demonstrated. The mechanization of this simulation required the use of techniques to compensate for the pitch attitude difference between the TIFS airplane and the configurations investigated during the approach task. The technique allowed the motion at the evaluation pilot station to be faithfully simulated. Techniques were also developed to simulate representative evaluation tasks including crosswind, lateral offset and glide slope errors. The pilot evaluation was based upon performing the entire landing approach mission, including localizer interception, glide slope tracking on instruments to visual breakout at 300 feet and flight under visual conditions to a simulated touchdown. A summary of the results and conclusions obtained from this research program is presented as follows:

(1) In general, the most critical task appeared to be longitudinal control in flare and touchdown. The major difficulties were related to the sluggish pitch attitude response and the high elevator activity ("pumping") required to control flight path in ground effect. The specific nature of the ground effect that was simulated introduced a strong pitch down motion which appeared to have a significant effect on the pilots' control difficulties in flare and touchdown. The ground effect used in this simulation was based upon data supplied by the FAA for a large delta-wing transport aircraft. The pilot ratings obtained in this program may be strongly influenced by the simulated ground effect.

(2) Tight attitude control was required to fly the mission for all statically unstable configurations. In flare and touchdown the pilot control technique required large pumping motions of the elevator to control attitude. On several approaches, the degrading influence of ground effect appeared to be reduced by ducking under the normal glide slope and flying a shallower flight path angle prior to touchdown.

(3) The general improvement in pilot rating and performance for similar configurations during the progress of the experiment indicates the possibility of a "learning curve" phenomenon. Thus the level of pilot training in controlling unaugmented large delta-wing transports in ground effect may have a significant effect on the ability to achieve acceptable touchdown performance.

(4) The experiment was conducted during day time, VFR conditions, with IFR conditions simulated. For those flights when visibility was restricted after breakout, pilot perception of attitude cues was diminished and resulted in an increase in pilot workload and a degradation in touchdown performance. Thus landing unaugmented large delta-wing transports under decreased

visibility and night time conditions could adversely affect pilot workload and control in the flare and touchdown.

(5) As the level of longitudinal instability was increased, turbulence effects became more significant on pilot workload, pilot performance and the acceptability of a configuration for the task. Specifically, the minimum acceptable boundary (Pilot Rating of 6.5 on the Cooper-Harper scale) determined in this investigation occurs at a T_2 = 2.5 seconds in light turbulence ($\sigma_{v_{g_{MAX}}}$ = 1.5 ft/sec) and at a T_2 = 4.25 seconds for moderate turbulence ($\sigma_{v_{g_{MAX}}}$ = 3.0 ft/sec).

(6) For the statically unstable configurations evaluated there appears to be no significant improvement in pilot rating as T_2 is increased above 6 seconds for both light and moderate turbulence. There appears to be a significant degradation in pilot rating as T_2 is decreased below 6 seconds. In general, these trends are consistent with the data described in Reference 2.

(7) For those configurations evaluated with a reduction in induced drag (airplane placed in the bucket of the power-required curve at the approach airspeed), a slight improvement in pilot rating was noted. This effect was more significant in moderate turbulence than in light turbulence and is related to a reduction in pilot workload to control airspeed on the approach.

(8) For the "backsided" configurations evaluated with nonlinear pitching moment effects, the pitch up tendency and increased longitudinal instability below trim speed was considered objectionable. Pilot attention to airspeed control was increased to avoid this objectionable behavior, however, no significant influence was noted on pilot rating.

(9) When ($C_{m_{\dot{\alpha}}} + C_{m_q}$) was increased with T_2 held constant, a slight degradation in pilot rating was noted. However, the data obtained indicates that an improvement in pilot rating would result from an increase in ($C_{m_{\dot{\alpha}}} + C_{m_q}$) at constant angle-of-attack stiffness (C_{m_α}), i.e., T_2 increased.

(10) An analysis of pitch attitude response to elevator commands indicated that the short term nature of pitch attitude can be examined by a constant speed short period approximation. For values of static instability above the value which yields a neutrally stable short term attitude response, the pilot rating degrades for moderate turbulence. For relatively light turbulence, a higher value of instability of the short term attitude response is achievable before pilot rating significantly degrades.

(11) There does not appear to be a direct correlation between pilot rating and individual touchdown performance parameters such as sink rate, touchdown distance, pitch attitude at touchdown and airspeed at touchdown. However, the data does indicate that as longitudinal control became more difficult in the flare and touchdown task, the pilot would permit degradation in all other touchdown parameters (e.g., increase in touchdown distance) in attempting to achieve a reasonable sink rate at touchdown.

(12) The time to double amplitude measured from angle of attack response (T_{2_α}) to an elevator input appears to be quite sensitive to the direction of control input especially for configurations with nonlinear aerodynamic derivatives.

(13) The results of this investigation are believed to be significantly influenced by the characteristics of the simulated ground effect, sluggishness of pitch response to elevator commands, pilot training and reduced visibility in the flare and touchdown.

APPENDIX I

CONFIGURATIONS

AERODYNAMICS OF THE CONFIGURATIONS

As discussed in Section II, the basic configuration as represented by the six equations of motion shown in Section II of Volume II, were modified to form the 20 configurations of the experiment. A more detailed description of the aerodynamics is presented in Section III of Volume II. The longitudinal equations can be written in the following generalized format:

$$-C_X = C_{D_0} + K_D C_{L_{NT_{IGE}}}^2 + \left[C_{D_{\alpha\delta_e}} \alpha + C_{D_{\delta_e}} + C_{D_{\delta_e^2}} \delta_e \right] \delta_e$$

$$+ F(d) K_{D_{GE}} C_{L_{NT_{IGE}}}^2 .$$

$$C_L = C_{L_0} + C_{L_\alpha} \alpha + C_{L_{\delta_e}} \delta_e + \left(C_{L_{\dot\alpha}} \dot\alpha + C_{L_q} q \right) \frac{\ell}{V}$$

$$+ F(d) \left[\Delta C_{L_{\alpha_{GE}}} \alpha + \Delta C_{L_{\delta_{e_{GE}}}} \delta_e \right].$$

$$C_m = C_{m_0} + C_{m_1} \alpha + C_{m_2} \alpha^2 + C_{m_3} \alpha^3 + C_{m_{\delta_e}} + \left[C_{m_{\dot\alpha}} \dot\alpha + C_{m_q} q \right] \frac{\ell}{V}$$

$$+ F_1(d) \left\{ \Delta C_{m_{0_{GE}}} + \left[\Delta C_{m_{\alpha_{GE}}} + .421 \left(C_{m_{\alpha_{CONFIG}}} - .00037 \right) \right] \alpha \right.$$

$$\left. + \Delta C_{m_{\delta_{e_{GE}}}} \delta_e \right\}.$$

Table I-I presents the variation of the stability derivatives for each of the configurations evaluated. For the three stable configurations, numbers 1, 13 and 20, the elevator control sensitivity was increased from the basic value of -0.00342 to -0.007 to provide the evaluation pilot with sufficient longitudinal control in ground effect. Also, the C_{m_3} derivative was set to zero for all the con .gurations. All the other changes were made for one or more of the following reasons:

TABLE I-I
LONGITUDINAL STABILITY DERIVATIVES AND CONSTANTS

CONFIG.	C_{m_o}	C_{m_1}	C_{m_2}	$\Delta C_{m_{\alpha GE}}$	$C_{m\delta_e}$	C_{m_q}	$C_{m_{\dot\alpha}}$	C_{D_o}	K_D	$K_{D_{GE}}$
1	.09162	-.00771	0	-.00500	-.00700	-.00257	-.00137	.03030	.324	-.1100
2	-.00563	-.00043	0	-.00264	-.00342	-.00257	-.00137	.03030	.324	-.1100
3	-.01019	-.00010	0	-.00250	-.00342	-.00257	-.00137	.03030	.324	-.1100
4	-.02082	.00067	0	-.00217	-.00342	-.00257	-.00137	.03030	.324	-.1100
5	-.05231	.00295	0	-.00121	-.00342	-.00257	-.00137	.03030	.324	-.1100
6	.00885	-.00286	.0001	-.00250	-.00342	-.00257	-.00137	.03030	.324	-.1100
7	.00178	-.00209	.0001	-.00217	-.00342	-.00257	-.00137	.03030	.324	-.1100
8	.02790	-.00562	.0002	-.00250	-.00342	-.00257	-.00137	.03030	.324	-.1100
9	.01726	-.00485	.0002	-.00217	-.00342	-.00257	-.00137	.03030	.324	-.1100
10	-.01019	-.00010	0	-.00250	-.00342	-.00257	-.00137	.08646	.196	-.0664
11	-.02082	.00067	0	-.00217	-.00342	-.00257	-.00137	.08646	.196	-.0664
12	-.05231	.00295	0	-.00121	-.00342	-.00257	-.00137	.08646	.196	-.0664
13	.09162	-.00771	0	-.00500	-.00700	-.01285	-.00685	.03030	.324	-.1100
14	-.01944	.00057	0	-.00222	-.00342	-.01285	-.00685	.03030	.324	-.1100
15	-.04333	.00230	0	-.00149	-.00342	-.01285	-.00685	.03030	.324	-.1100
16	-.09816	.00627	0	.00018	-.00342	-.01285	-.00685	.03030	.324	-.1100
17	.01864	-.00495	.0002	-.00222	-.00342	-.01285	-.00685	.03030	.324	-.1100
18	-.00525	-.00322	.0002	-.00149	-.00342	-.01285	-.00685	.03030	.324	-.1100
19	-.06007	.00075	.0002	.00018	-.00342	-.01285	-.00685	.03030	.324	-.1100
20	.09162	-.00771	0	.00500	-.00700	-.01285	-.00685	.08646	.196	-.1100

NOTE: THE FOLLOWING DERIVATIVES WERE HELD CONSTANT FOR ALL CONFIGURATIONS:

$C_{D_{\alpha\delta_e}}$ = .000296 $C_{L_{\delta_e}}$ = .01184 C_{m_3} = 0.0

$C_{D_{\delta_e}}$ = -.000838 $C_{L_{\dot\alpha}}$ = .00575 $\Delta C_{m_{o_{GE}}}$ = .0059

$C_{D_{\delta_e^2}}$ = .0000494 $\Delta C_{L_{\alpha GE}}$ = .0210 $\Delta C_{m_{\delta_{e_{GE}}}}$ = -.00038

C_{L_o} = -.177 $\Delta C_{L_{\delta_{e_{GE}}}}$ = .00262

C_{L_α} = .0606 C_{L_q} = .00548

Units are in degrees and feet/second

1. To vary the time to double amplitude

2. To modify the linearity of the C_m versus α curve around the trim point.

3. To change from the backside to the bottom of the power required curve, and

4. To increase the pitch damping $\left(C_{m_{\dot{\alpha}}} + C_{m_q}\right)$ to five times the normal damping.

DIMENSIONAL STABILITY DERIVATIVES

Table I-II lists the longitudinal dimensional stability derivatives and the control derivatives out of the influence of ground effect for each of the configurations evaluated in this research program. It should be noted that the seven configurations characterized by the nonlinear variation of pitching moment with angle of attack have identical dimensional stability derivatives as the linear configurations with the same time to double amplitude of the unstable root.

Table I-III presents the lateral-directional dimensional stability derivatives and the control derivatives that were used for all twenty configurations of this experiment.

In Table I-IV are shown the variations of the longitudinal dimensional stability derivatives due to ground effect for Configurations 3, 4 and 5. These particular configurations were selected because they were indicative of the range in T_2 of the unstable mode. The data were computed at six different c.g. heights, namely 400, 200, 50, 25 and 16 feet. Since the c.g. is located approximately 14.5 feet above the ground, then the lowest height corresponds to the wheels of the main landing gear being 18 inches above the runway.

CHARACTERISTIC MODES AND TRANSFER FUNCTION NUMERATORS

Table I-V lists the characteristic modes and the θ/δ_e, α/δ_e and V/δ_e transfer function numerators for all the configurations of this experiment. Because the data were obtained from the linearized dimensional stability derivatives of Table I-II, only 13 unique variations are presented.

DIGITAL RESPONSE TO STEP ELEVATOR INPUTS

Figures I-2 through I-4 present selected groups of digital responses to a one degree step elevator input in the nose-up direction. The parameters shown, $\Delta\alpha$, $\Delta\theta$, q, ΔV and Δn_y, were computed at the center of gravity position of the model.

The grouping of the time history sets was not done in a numerical sequence by configuration number but in a special pattern. This procedure was followed to facilitate the comparison, as much as possible, between the set of responses of a configuration that was different by just one variable with sets of responses of another configuration that was to the left or right or above or below. For example, the time history set for Configuration 4 which was a T_2 of 4 seconds was located between the time history sets for Configuration 3 with a T_2 of 8 seconds and Configuration 5 with a T_2 of 2 seconds. Furthermore, Configuration 4 which was on the backside of the power required curve was situated above Configuration 11 which was on the bottom of the power required curve and, like Configuration 4, also had a T_2 of 4 seconds.

TABLE I-II

LONGITUDINAL DIMENSIONAL DERIVATIVES
(STABILITY AXES)
OUT OF GROUND EFFECT

CONFIG.	D_α	D_θ	D_V	D_{δ_x}	D_{δ_e}	Z_α	$Z_V \times 10^3$	Z_q	$Z_{\dot\alpha}$	Z_{δ_x}	Z_{δ_e}	M_α	$M_V \times 10^4$	M_q	$M_{\dot\alpha}$	M_{δ_x}	M_{δ_e}
1	30.186	32.2	.05818	-13.709	8.4856	-.62918	-.8196	-.018172	-.019067	-.013484	-.11725	-.89284	-.6561	[illegible]	-.053127	.015608	-.81862
2	30.337	32.2	.0584	-13.704	8.4325	-.62929	-.819	-.018172	-.019067	.013563	-.11725	-.340786	[illegible]	[illegible]	-.053127	.015608	-.39605
3 (6, 8)	30.328	32.2	.05830	-13.704	8.4263	-.62929	-.8191	-.018172	-.019067	-.013659	-.11725	-.011580	-.65874	[illegible]	-.053127	.015608	-.39605
4 (7, 9)	30.307	32.2	.05836	-13.705	8.4415	-.62938	-.8192	-.018172	-.019067	[illegible]	-.11725	.077580	-.65841	[illegible]	-.053127	.015608	-.39605
5	30.256	32.2	.05829	-13.707	8.4576	-.62924	-.8193	-.018172	-.019067	-.01353	-.11725	.34162	-.65066	[illegible]	-.053127	.015608	-.39605
10	11.15	32.2	.05725	-13.704	8.4486	-.62882	-.8198	-.018172	-.019067	-.01357	-.11725	-.011580	-.65246	[illegible]	-.052127	.015608	-.39605
11	11.153	32.2	.05786	-13.704	8.4480	-.62882	-.8198	-.018172	-.019067	-.013561	-.11725	.077580	-.65240	[illegible]	-.053127	.015608	-.39605
12	11.16	32.2	.05767	-13.706	8.4629	-.62883	-.8198	-.018172	-.019067	-.013538	-.11725	.34162	-.65256	[illegible]	-.052127	.015608	-.39605
13	30.186	32.2	.05818	-13.709	8.4856	-.62918	-.8196	-.018172	-.019067	-.013494	-.11725	-.89284	-.65814	-.48831	-.28564	.015608	-.81862
14 (17)	30.31	32.2	.05836	-13.705	8.4407	-.62928	-.8192	-.018172	-.019067	-.013552	-.11725	.084008	-.66045	-.49831	-.28564	.015536	-.39605
15 (18)	30.289	32.2	.05831	-13.706	8.4535	-.62925	-.8193	-.018172	-.019067	-.013536	-.11725	.28635	-.65079	-.49831	-.28564	.015608	-.39605
16 (19)	30.198	32.2	.05827	-13.708	8.4758	-.62920	-.8195	-.018172	-.019067	-.013507	-.11725	.72608	-.65865	-.48831	-.28564	.015608	-.39605
20	11.173	32.2	.05789	-13.708	8.4886	-.62894	-.8201	-.018172	-.019067	-.013501	-.11725	-.89284	-.65268	-.48831	-.28564	.015608	-.81862

TABLE I-III

LATERAL-DIRECTIONAL DIMENSIONAL DERIVATIVES
(BODY AXES)
OUT OF GROUND EFFECT

	Y_β	$Y_{\dot\beta}$	Y_p	Y_r	Y_{δ_a}	Y_{δ_r}	L_β	$L_{\dot\beta}$	L_p	L_r	L_{δ_a}	L_{δ_r}	N_β	$N_{\dot\beta}$	N_p	N_r	N_{δ_a}	N_{δ_r}	$\frac{N_{\delta_a}}{L_{\delta_a}}$
ALL CONFIGS.	-.08843	-.007512	.00412	.01116	.01661	.02277	-2.6483	-.008447	-.86480	.30660	-1.9566	.33942	.20792	.031704	-.00450	-.10188	-.07722	-.18021	.03946

LATERAL-DIRECTIONAL MODAL PARAMETERS

OUT OF GROUND EFFECT

ω_{DR} = .9236 RAD/SEC $\quad \zeta_{DR}$ = .1792 $\quad \tau_R$ = 1.873 SEC $\quad \tau_S$ = 23.38 SEC $\quad |\phi/\beta|_{DR}$ = 2.738 $\quad \angle\phi/\beta_{DR}$ = 213.3 DEG

ω_ϕ = .5744 RAD/SEC $\quad \zeta_\phi$ = .2375

TABLE I-IV

LONGITUDINAL DIMENSIONAL DERIVATIVES (STABILITY AXES) CONFIGURATIONS 3, 4 & 5 IN GROUND EFFECT

CONFIG.	h_{CG}	D_α	D_θ	D_V	D_{δ_x}	D_{δ_e}	Z_α	$Z_V \times 10^3$	Z_q	$Z_{\dot\alpha}$	Z_{δ_x}	Z_{δ_e}	M_α	$M_V \times 10^4$	M_q	$M_{\dot\alpha}$	M_{δ_x}	M_{δ_e}
3	400	39.328	32.2	.058388	13.704	8.4353	.62929	.8191	.018172	-.019067	.013569	-.11725	-.01158	-.6607	-.099662	-.053127	.015508	-.38605
	200	39.028	32.2	.058032	13.713	8.308	-.63328	-.82	.018172	-.019067	-.013446	-.11777	-.014474	-.6563	-.099662	-.053127	.015508	-.38649
	100	39.049	32.2	.057231	13.731	8.0129	.64772	.8210	.018172	.019067	.013195	.11962	.023313	-.6464	.099662	-.053127	.015508	-.39783
	50	39.132	32.2	.055876	13.758	7.5411	-.67354	.8245	-.018172	-.019067	-.012806	.12292	.040344	-.6299	-.099662	-.053127	.015508	-.40042
	25	38.777	32.2	.057874	13.804	6.3258	.74173	.8305	.018172	-.019067	-.012102	.13162	.13517	-.5940	-.099662	-.053127	.015508	-.41485
	16	36.519	32.2	.049651	13.827	5.2276	.8107	.8353	.018172	.019067	.011578	.14042	.25942	-.5565	-.099662	-.053127	.015508	-.43375
4	400	39.307	32.2	.058362	13.705	8.4415	.62928	.8192	.018172	-.019067	.013551	.11725	.077588	.6604	-.099662	-.053127	.015508	-.38605
	200	36.013	32.2	.058013	13.713	8.3125	.63327	.82	.018172	.019067	.013441	.11777	.075089	-.6561	-.099662	-.053127	.015508	-.38649
	100	39.044	32.2	.057224	13.731	8.0145	.64771	.8219	-.018172	.019067	.013193	.11962	.067317	-.6463	-.099662	-.053127	.015508	-.39783
	50	39.138	32.2	.055823	13.757	7.5395	.67354	.8249	.018172	.019067	.012808	.12292	.052556	-.63	-.099662	-.053127	.015508	-.40042
	25	38.885	32.2	.052743	13.806	6.3405	.74167	.8308	.018172	.019067	.012075	.13162	-.039874	-.5825	-.099662	-.053127	.015508	-.41486
	16	36.369	32.2	.049261	13.842	5.2313	.81052	.8359	.018177	.019067	.011506	.14042	.1381	.5522	-.099662	-.053127	.015508	-.43375
5	400	39.256	32.2	.058295	13.707	8.4576	.62924	.8193	.018172	.019067	.013530	.11725	.34162	-.6596	-.099662	.053127	.015508	-.38605
	200	38.976	32.2	.057965	13.714	8.3239	.63324	.8201	.018172	.019067	.013476	-.11777	.34021	-.6555	-.099662	-.053127	.015508	-.38649
	100	39.029	32.2	.057205	13.731	8.0186	.647[illegible]	.8219	.018172	.019067	.013188	.11962	.33592	-.6461	-.099662	-.053127	.015508	.39783
	50	39.152	32.2	.055903	13.757	7.5355	.67355	.8248	.018172	.019067	.012813	-.12292	.32764	-.6302	-.099662	-.053127	.015508	-.40042
	25	38.665	32.2	.052439	13.81	6.4007	.74151	.8313	.018172	.019067	.012007	.13162	.28155	-.5889	-.099662	-.053127	.015508	.41485
	16	35.649	32.2	.048393	13.852	5.4453	.81007	.8373	.018172	.019067	.011328	.14042	.22117	-.5418	-.099662	-.053127	.015508	-.43375

TABLE I-V

LONGITUDINAL TRANSFER FUNCTION FACTORS FOR THE EVALUATION CONFIGURATIONS OUT OF GROUND EFFECT

PARAMETER		CONFIGURATIONS												
		1	2	3 (6, 9)	4 (7, 8)	5	10	11	12	13	14 (17)	15 (18)	16 (19)	20
Δ	$1/T_{SP_1}$ (ζ_{SP})	(.4225)	.1926	-.08551	.1656	-.3446	-.07096	-.1497	-.3291	(.6516)	-.06366	-.1858	-.3465	(.6443)
	$1/T_{SP_2}$ (ω_{SP})	(.9410)	.6328	.7030	.822	1.056	.6725	.7997	1.041	(1.079)	1.186	1.354	1.631	(1.082)
	ζ_3 $(1/T_{PH_1})$ (ζ_{PH})	(.0995)	(.01508)	.8055	.5452	.3441	.7753	.5286	.3294	(.08841)	.9424	.6303	.3843	(.1281)
	ω_3 $(1/T_{PH_2})$ (ω_{PH})	(.1570)	(.01378)	.1299	.1562	.167	.1445	.1662	.1721	(.1369)	.1742	.1914	.1886	(.1366)
$N^{\theta}_{\delta_e}$	A_{θ}	.8045	.39	.39	.78	.39	.39	.39	.39	.78	.3656	.3656	.3656	.78
	$1/T_{\theta_1}$	.008342	.00664	.008516	.006241	.005513	04126	.03946	.03497	.008338	.006272	.005705	.004639	.05344
	$1/T_{\theta_2}$	.544	.6638	.6751	.7017	.7802	.6393	.6674	.7499	.5614	.7454	.809	.9546	.5155
$N^{\alpha}_{\delta_e}$	A_{α}	.115	.115	.115	.115	.115	.115	.115	.115	.115	.115	.115	.115	.115
	$1/T_{\alpha_1}$	6.833	3.367	3.367	3.367	3.367	3.367	3.367	2.367	7.236	3.77	3.77	3.77	7.236
	ζ_{α}	.1638	.1507	.1507	.1506	.1504	.1483	.1483	.1483	.1597	.1445	.1443	.1439	.1581
	ω_{α}	.1625	.1607	.1607	.1607	.1607	.1608	.1608	.1608	.1579	.1519	.1519	.1519	.1579
$N^{v}_{\delta_e}$	A_v	8.486	8.433	8.436	8.442	8.458	8.441	8.447	8.463	8.486	8.442	8.454	8.476	8.488
	$1/T_{v_1}$	2.383	1.762	1.77	1.791	1.851	1.495	1.525	1.61	2.719	2.126	2.171	2.274	2.218
	$1/T_{v_2}$	.261	.2852	.2872	.2918	[illegible]	.4625	.4621	.4611	.2597	.287	.2961	.3135	.4647
	$1/T_{v_3}$	2.417	1.815	1.826	-1.850	1.921	-1.341	1.371	-1.454	-2.138	-1.577	-1.63	-1.746	-1.463

$$\Delta = (s^2 + 2\zeta_{SP}\omega_{SP}s + \omega_{SP}^2)(s^2 + 2\zeta_{PH}\omega_{PH}s + \omega_{PH}^2);\ \left(s+\frac{1}{T_{SP_1}}\right)\left(s+\frac{1}{T_{SP_2}}\right)\left(s+\frac{1}{T_{PH_1}}\right)\left(s+\frac{1}{T_{PH_2}}\right);\ \left(s+\frac{1}{T_{SP_1}}\right)\left(s+\frac{1}{T_{SP_2}}\right)(s^2+2\zeta_3\omega_3 s+\omega_3^2)$$

$$N^{\theta}_{\delta_e} = -A_{\theta}\left(s+\frac{1}{T_{\theta_1}}\right)\left(s+\frac{1}{T_{\theta_2}}\right)$$

$$N^{\alpha}_{\delta_e} = -A_{\alpha}\left(s+\frac{1}{T_{\alpha_1}}\right)(s^2+2\zeta_{\alpha}\omega_{\alpha}s+\omega_{\alpha}^2)$$

$$N^{v}_{\delta_e} = -A_v\left(s+\frac{1}{T_{v_1}}\right)\left(s+\frac{1}{T_{v_2}}\right)\left(s+\frac{1}{T_{v_3}}\right)$$

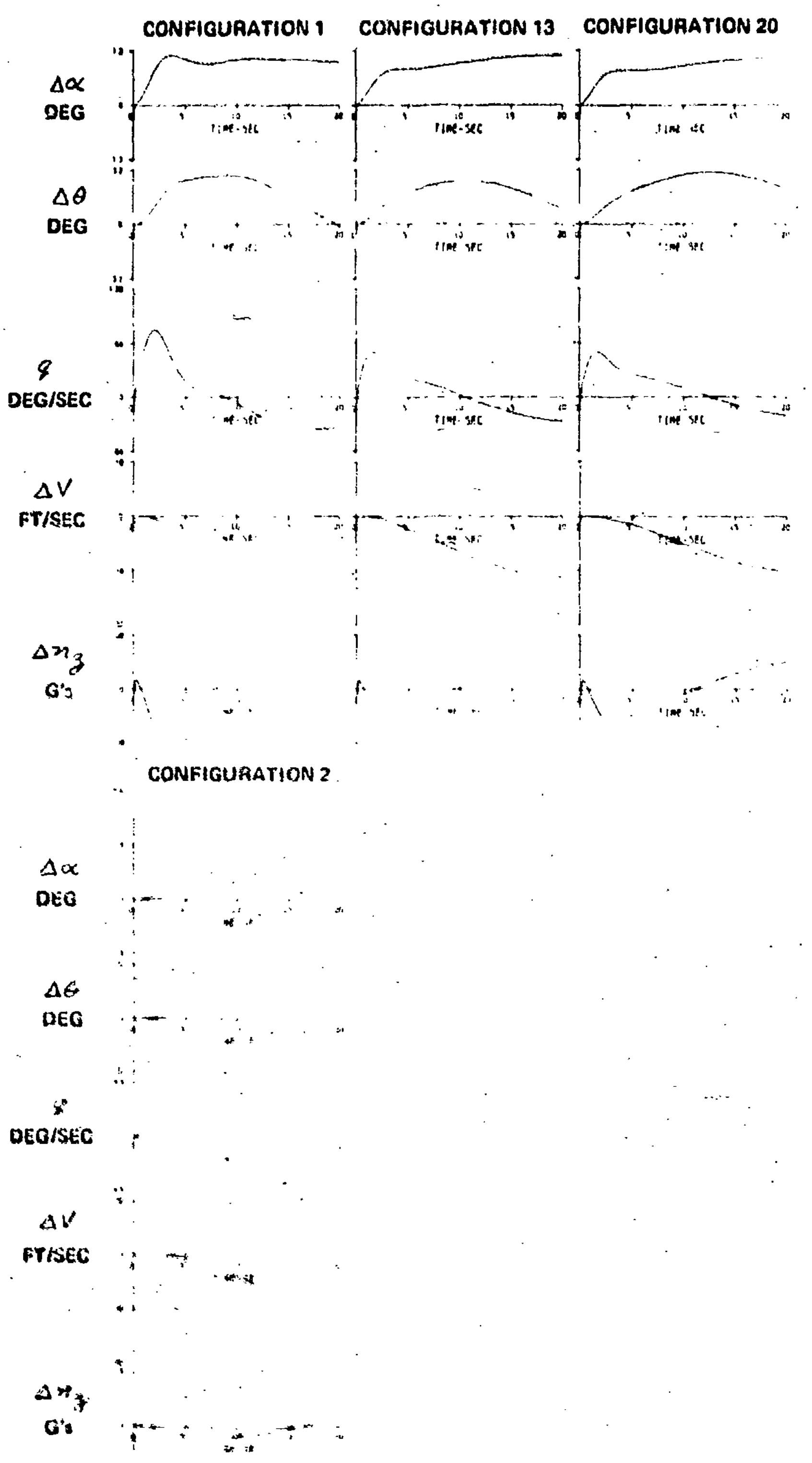


Figure I-1 DIGITAL RESPONSES TO A ONE DEGREE STEP ELEVATOR INPUT IN THE NOSE-UP DIRECTION

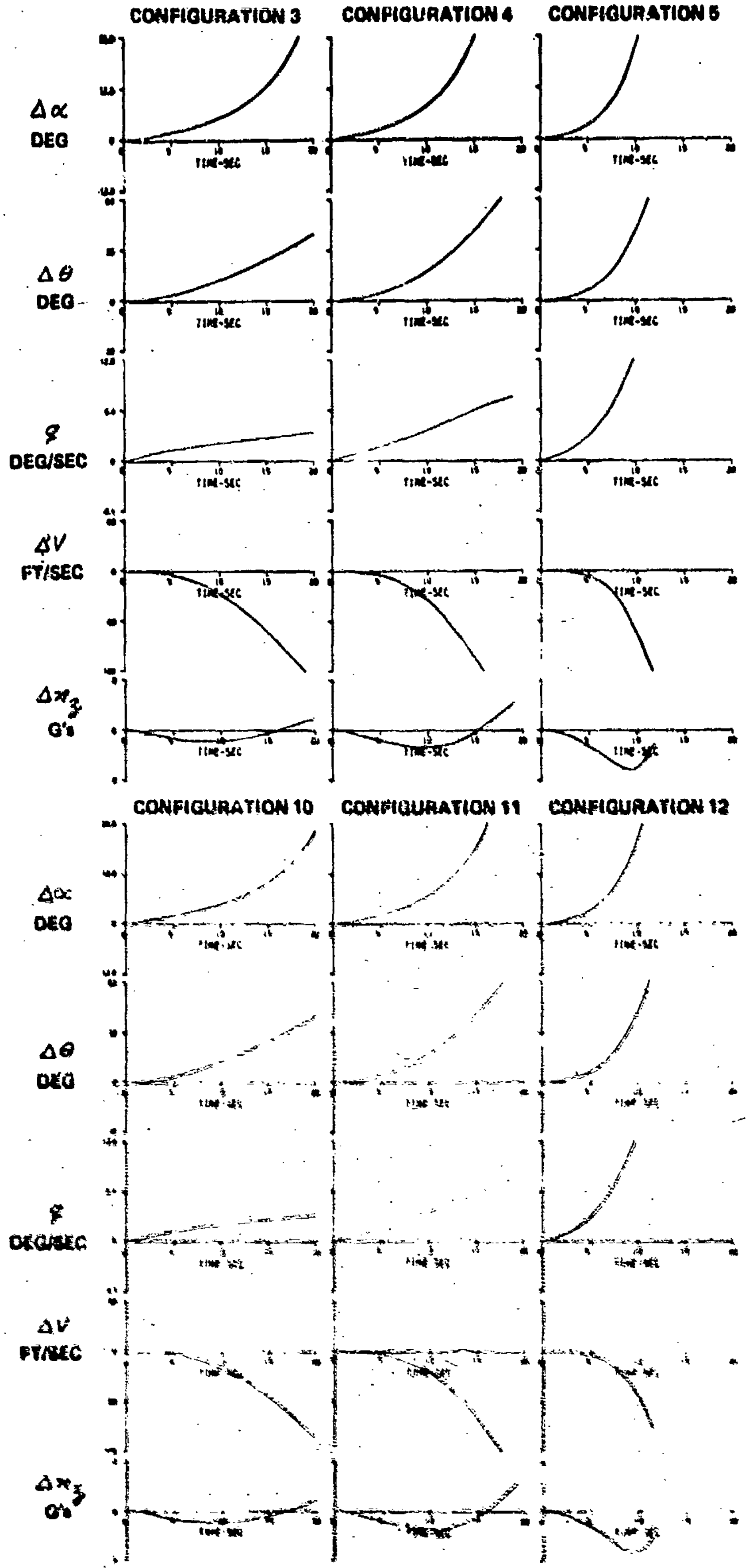


Figure I-2 DIGITAL RESPONSES TO A ONE DEGREE STEP ELEVATOR INPUT IN THE NOSE-UP DIRECTION

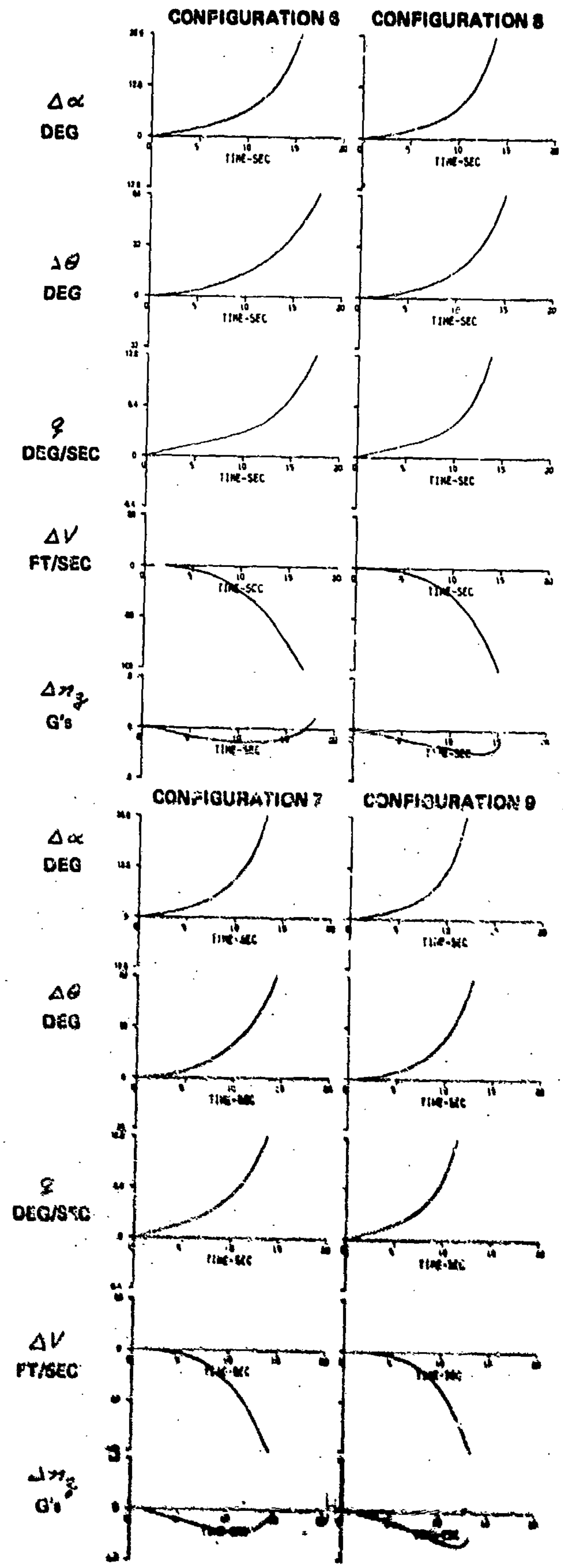


Figure I-3 DIGITAL RESPONSES TO A ONE DEGREE STEP ELEVATOR INPUT IN THE NOSE-UP DIRECTION

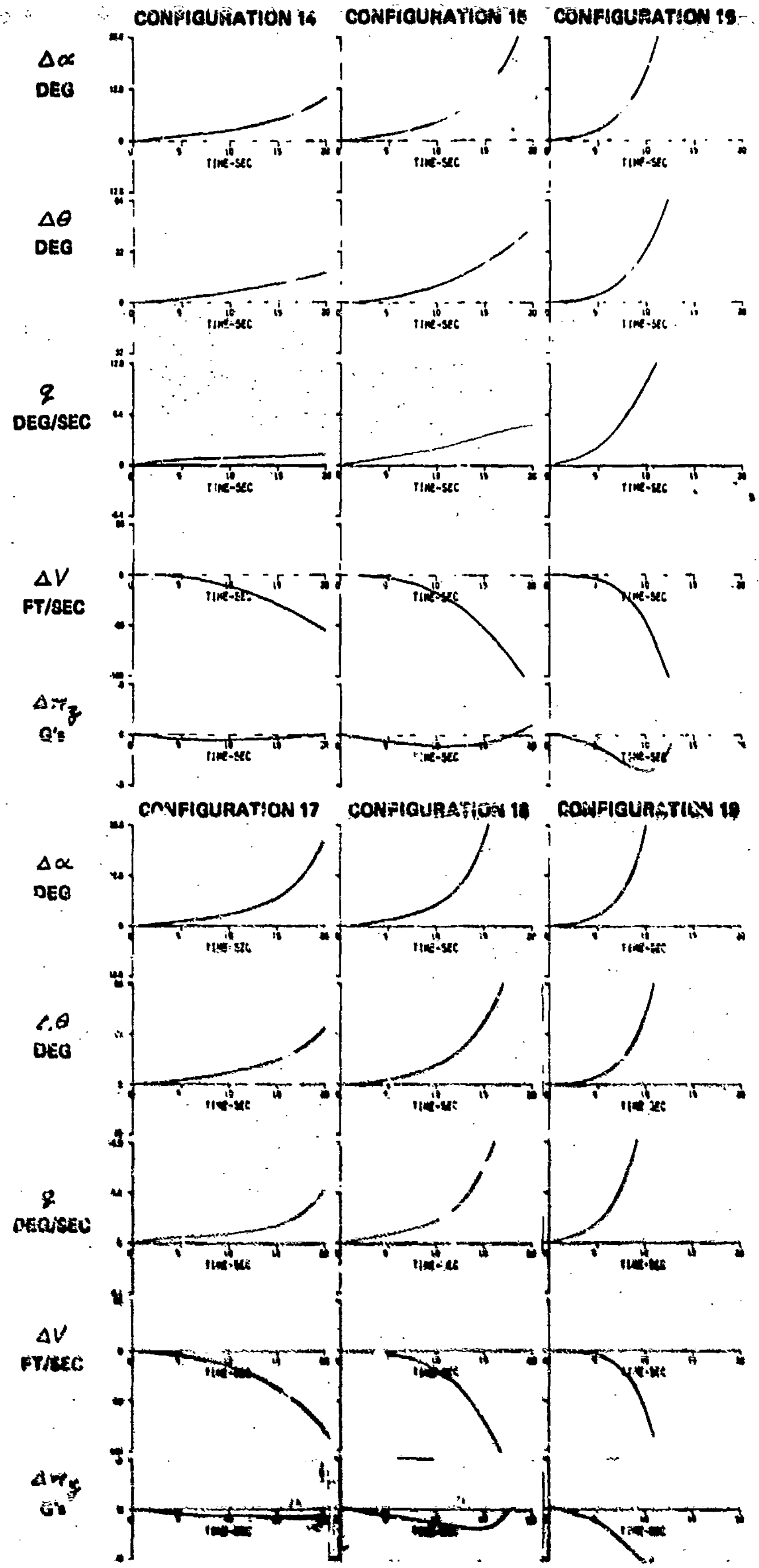


Figure I-4 DIGITAL RESPONSES TO A ONE DEGREE STEP ELEVATOR INPUT IN THE NOSE-UP DIRECTION

APPENDIX II

REVIEW OF CLASSICAL STABILITY CONCEPTS

The purpose of this section is to review some basic concepts of stability and control and to apply these concepts to the airplane configurations evaluated in this research program. The following paragraphs will review such concepts, for example, as static stability, maneuver margin, dynamic stability, time to double amplitude, and flight path stability.

LINEARIZED EQUATIONS OF MOTION

Prior to a discussion of the various stability concepts, it is of value to establish a definition of the terms to be reviewed, and the definitions of the various stability and control derivatives that will be used. In order to accomplish this, it is first necessary to cast the equations of motion into a form that illustrates the definitions of the stability and control derivatives. This is accomplished by a linearization (first order perturbation analysis) of the equations of motion. Since the subject of interest is longitudinal stability, only the linearized form of the longitudinal equations will be presented.

DRAG EQUATION

$$\Delta\dot{V} + D_\theta \,\Delta\theta + D_V \,\Delta V + D_\alpha \,\Delta\alpha = -D_{\delta_x}\,\Delta\delta_x - D_{\delta_e}\,\Delta\delta_e \qquad \text{(II.1)}$$

where

$$D_\theta = g\cos\gamma_0$$

$$D_V = \frac{\rho_0 V_0 S}{m} C_{D_t} - \frac{\partial T}{\partial V}\frac{\cos(\alpha_I + i_T)_0}{m}$$

$$D_\alpha = \frac{1}{m}\left[\frac{\rho_0 V_0^2 S}{2} C_{D_\alpha} + T_0 \sin(\alpha_I + i_T)_0 - W\cos\gamma_0\right]$$

$$D_{\delta_x} = -\frac{1}{m}\frac{\partial T}{\partial \delta_x}\cos(\alpha_I + i_T)_0$$

$$D_{\delta_e} = \frac{\rho_0 V_0^2 S}{2m} C_{D\delta_e}$$

where $$C_{D_t} = \frac{-W \sin \gamma_0 + T_0 \cos(\alpha_I + i_T)}{\bar{q}_0 S}$$

and $C_{D_{\bar{\alpha}}}$, $C_{D\bar{\delta}_e}$ represent these derivatives linearized about the particular trim condition $(\alpha_{I_0}, \delta_{e_0})$

LIFT EQUATION

$$(1-Z_{\dot{\alpha}})\Delta\dot{\alpha} - (1+Z'_q)\Delta\dot{\theta} - Z_\theta\Delta\theta - Z_V\Delta V - Z_\alpha\Delta\alpha$$
$$= Z_{\delta_e}\Delta\delta_e + Z_{\delta_x}\Delta\delta_x \qquad \text{(II.2)}$$

where

$$Z_{\dot{\alpha}} = -\frac{1}{mV_0}\left[\bar{q}_0 S \frac{\ell}{V_0} C_{L\dot{\alpha}}\right]$$

$$Z_q = -\frac{1}{mV_0}\left[\bar{q}_0 S \frac{\ell}{V_0} C_{Lq}\right]$$

$$Z_\theta = -\frac{g}{V_0} \sin \gamma_0$$

$$Z_V = -\frac{1}{mV_0}\left[\rho_0 V_0 S C_{Lt} + \frac{\partial T}{\partial V} \sin(\alpha_I + i_T)_0\right]$$

$$Z_\alpha = -\frac{1}{mV_o}\left[\bar{q}_o S C_{L_\alpha} + T_o \cos(\alpha_I + i_T)_o - W \sin \gamma_o\right]$$

$$Z_{\delta_e} = -\frac{1}{mV_o}\left(\bar{q}_o S C_{L_{\delta_e}}\right)$$

$$Z_{\delta_x} = -\frac{1}{mV_o}\left(\frac{\partial T}{\partial \delta_x} \sin(\alpha_I + i_T)_o\right)$$

where $C_{L_t} = \dfrac{W \cos \gamma_o - T_o \sin(\alpha_I + i_T)_o}{\bar{q}_o S}$

PITCHING MOMENT EQUATION

$$\Delta\ddot{\theta} - M_q \Delta\dot{\theta} - M_V \Delta V - M_{\dot{\alpha}} \Delta\dot{\alpha} - M_\alpha \Delta\alpha = M_{\delta_e}\Delta\delta_e + M_{\delta_x}\Delta\delta_x \qquad \text{(II.3)}$$

where

$$M_q = \frac{\bar{q}_o S \ell^2}{I_{yy} V_o} C_{m_q}$$

$$M_{\dot{\alpha}} = \frac{\bar{q}_o S \ell^2}{I_{yy} V_o} C_{m_{\dot{\alpha}}}$$

$$M_V = \frac{\bar{q}_o S \ell}{I_{yy}}\left[\frac{2}{V_o} C_{m_t} + C_{m_V}\right] + \frac{\bar{z}_T}{I_{yy}} \frac{\partial T}{\partial V}$$

$$M_\alpha = \frac{\bar{q}_o S \ell}{I_{yy}} C_{m_\alpha}$$

$$M_{\delta_e} = \frac{\bar{q}_o S \ell}{I_{yy}} C_{m_{\delta_e}}$$

$$M_{\delta_x} = \frac{\bar{z}_T}{I_{yy}} \frac{\partial T}{\partial x}$$

$$C_{m_t} = -\frac{\bar{z}_T}{\bar{c}} \frac{T_o}{\bar{q}_o S}$$

where

GENERALIZED CRITERION FOR STATIC LONGITUDINAL STABILITY

As discussed in Reference 1, the most general criterion for static longitudinal stability is not pitch stiffness, but the constant term in the longitudinal characteristic equation. The vanishing of this term yields a neutrally stable airplane, and when the constant term is negative a divergence occurs and the airplane will be statically unstable. It can be shown, based on the equations just presented, that the constant term of the longitudinal characteristic equation is:

$$E = -C_{L_t} C_{m_\alpha} + C_{m_t}(C_{L_\alpha} + C_{D_t}), \text{ assuming } C_{m_V} = \frac{\partial T}{\partial V} \equiv 0 \tag{II.4}$$

An aperiodic divergence can occur even for the aircraft with positive pitch stiffness $(C_{m_\alpha} < 0)$ when the thrust offset produces a destabilized effect $(C_{m_t} < 0)$. Thus the rate of divergence of this aperiodic mode of response (time to double amplitude) is a general measure of the static longitudinal stability. From the linearized equations of motion, solution of the characteristic equation will yield the root locations (poles) which will characterize the subsequent motion of the airplane. The presence of a root in the right-half part of the 's'-plane is associated with the negative value of the constant term of the characteristic equation, and the time to double amplitude (T_2) can be defined as $T_2 = \frac{\ln 2}{\lambda}$, where λ is the magnitude of the unstable root. While this concept is relatively easy, the difficulty occurs in attempting to measure this quantity when the motion of the airplane is forced by a specific control input. From the transfer function information presented in Appendix I, a reasonable candidate to determine the time to double amplitude of the unstable mode would be the angle of attack response to an elevator command. Since the oscillatory poles and zeros in the transfer of α/δ_e are in close proximity (see Table I-V) then an approximation to the transfer function can be written as:

$$\frac{\Delta\alpha}{\Delta\delta_e}(s) = \frac{s + a_\alpha}{(s+\lambda_1)(s+\lambda_2)} \tag{II.5}$$

and the time histories to an impulse and a step command can be expressed as:

impulse:

$$\Delta\alpha_p(t) = Ae^{-\lambda_1 t} + Be^{-\lambda_2 t} \tag{II.6}$$

step: $$\Delta\alpha_s(t) = \frac{A}{\lambda_1}\left(1-e^{-\lambda_1 t}\right) + \frac{B}{\lambda_2}\left[1-e^{-\lambda_2 t}\right] \tag{II.7}$$

If λ_1 is considered to be the unstable mode and λ_2 the stable mode, then as $t \to \infty$

$$\Delta\alpha_p(t) \to Ae^{-\lambda_1 t} \tag{II.8}$$

$$\Delta\alpha_s(t) \to \frac{A}{\lambda_1}\left[1-e^{-\lambda_1 t}\right] + \frac{B}{\lambda_2} = Ce^{-\lambda_1 t} + D \tag{II.9}$$

Since in general it is not possible in practical flight testing to wait for long periods of time to measure the unstable mode, a comparison was made using a linearized three-degree-of-freedom digital program to compare the value of T_2 as determined from the characteristic root location and the angle of attack time history to a step elevator command. Based on the form of the approximate time history of $\Delta\alpha(t)$ for a step, the following terms were used in the computation of T_2, $\Delta\alpha(t_n+1)-\Delta\alpha(t_n)$, and $\Delta\dot{\alpha}(t_n)$. The restriction placed on the computation was that $|\Delta\alpha_{max}| \leq 6°$, and $|\Delta V_{max}| \leq .1V_0$. Table II-I presents the results obtained from this analysis for T_2. The measured values were obtained from semi-log plots of the data.

For the longer time to double amplitude configurations, sufficient time history of response to determine T_2 is not available within the limitations imposed above. This difficulty could be removed by selecting a time history of control input which only excites the unstable mode, or by measuring the time to double amplitude of the response as the airplane drifts off the trim point. The results of the computation of T_2 from allowing the configurations to drift off the trim point, using turbulence as an excitation, are presented in Table II-II. The drift results were obtained from ground simulation studies on the TIFS airplane.

In order to evaluate these measures for a more realistic situation, a similar study was conducted using a six-degree-of-freedom nonlinear digital program, since all of the configurations evaluated have a nonlinear drag polar, and several have a nonlinear C_{m_α} curve. The results of this study are shown in Table II-II, for a negative elevator surface step using the previously cited restrictions on the data analyzed.

For the configurations with nonlinear C_{m_α}, the difficulties with the measure of T_2 are dependent upon the direction of the drift. If the airplane drifts nose up for these configurations, the measured T_2 will be realistic; however, if the configuration drifts nose down, then the measured

Table II-I

Time to Double Amplitude (T_2) Seconds from Linearized Equations of Motion

Conf.	T_2 based on Unstable root location	$^*\alpha(t_{n+1})-\alpha(t_n)$	$\dot{\alpha}(t_n)$
2	59.6	9.0	10.0
3	8.12	6.5	6.8
4	4.17	4.3	4.2
5	2.00	2.0	2.0
10	9.73	7.5	7.5
11	4.61	4.2	4.0
12	2.10	2.1	2.1
14	8.21	6.9	7.2
15	4.17	4.1	4.2
16	1.99	2.0	2.0

* where $\alpha(t_{n+1})-\alpha(t_n)$ indicates the difference between the angle of attack response at time t_{n+1} seconds from that at time t_n seconds.

Table II-II

T_2 ~ Seconds (Non-Linear Equations of Motion)

Conf.	T_2 based on $\alpha(t_{n+1})-\alpha(t_n)$	$\dot{\alpha}(t_n)$	Drift computation	Linearized Unstable root
2	7.2	6.7	21.5	59.6
3	6.2	6.0	8.0	8.12
4	4.1	4.2	*4.0	4.17
5	2.0	2.0	*2.1	2.0
6+	4.0	3.6	8.8	8.12
7+	3.1	3.2	4.5	4.17
8+	3.1	2.8	12.5	8.12
9+	2.7	2.4	*3.0	4.17
10	7.1	6.6	*8.6	9.73
11	4.6	4.3	1.5	4.61
12	2.1	2.0	*2.0	2.10
14	5.9	5.7	9.0	8.21
15	4.2	4.0	4.2	4.17
16	2.0	2.0	*2.6	1.99
17+	4.8	4.4	13.5	8.21
18+	3.4	2.9	5.5	4.17
19+	1.8	1.8	*1.95	1.99

Note * Nose-up drift

\+ Non-linear C_{m_α} configuration

T_2 will be longer than the value determined from other measurement techniques. Thus if time to double amplitude of the aperiodic mode of response is to be used as a criterion for minimum longitudinal stability, then care must be exercised in prescribing the measurement technique and the input (or disturbance) to be used.

EXAMINATION OF ATTITUDE RESPONSE AND THE UTILIZATION OF A SHORT TERM APPROXIMATION TO THE ATTITUDE RESPONSE

It has been postulated in several studies that a fundamental inner loop closure performed by the pilot in the landing approach task is on pitch attitude (References 15, 16, 17). Recently, Reference 18 developed a performance criterion for attitude tracking applied to the landing approach task. Closed loop analysis of attitude is examined in Section VIII of Volume II. This section will examine open-loop pitch attitude response for the configurations evaluated in this program, and will show that a short time approximation can indeed be used to represent the initial attitude response to an elevator command for the configurations investigated. Figures II-1, II-2, and II-3 represent the effects of changes in the parameters investigated on the time history of pitch rate to a negative unit elevator surface step command obtained from a six-degree-of-freedom nonlinear digital program. Examination of these figures yields the following information. First, in order to command pitch attitude it is necessary for the pilot to use a sequence of commands. In order to command an attitude change, the pilot must pulse the elevator to initiate a pitch rate and as the attitude approaches the desired value, he must then pulse the control in the opposite direction to stop at the desired attitude. Tight attitude control would then result in essentially a quick sequence of pulse-in, pulse-out commands, in other words, the pilot would have to "pump" the elevator control when attempting to tightly control airplane attitude as required in the landing approach task. In general, the responses illustrated on these figures also indicate that attitude response to an elevator pulse appears to be a first order response of the form $A(1 - e^{\lambda t})$. Figure II-1 indicates that at least for the few seconds following the control input, there appears to be no significant difference in the responses of Configurations 2, 3, and 4, while the response of Configuration 5 shows a strong divergence. Figure II-2 illustrates the effects of reducing induced drag and increasing $C_{m_q} + C_{m_{\dot{\alpha}}}$ on the pitch rate response to an elevator step command for configurations that would have an 8 second and 4 second time to double amplitude divergent mode of response based on characteristic root location. The reduction of induced drag used in this investigation does not have any significant effect on the short term attitude response, while increasing "pitch" damping $C_{m_q} + C_{m_{\dot{\alpha}}}$ at constant T_2 tends to increase the "equivalent" first-order time constant of the short term attitude response. While there is an increase in the pitch-up tendency of the airplane with nonlinear C_{m_α}, this effect does not tend to manifest itself in the attitude response until several seconds after the control input.

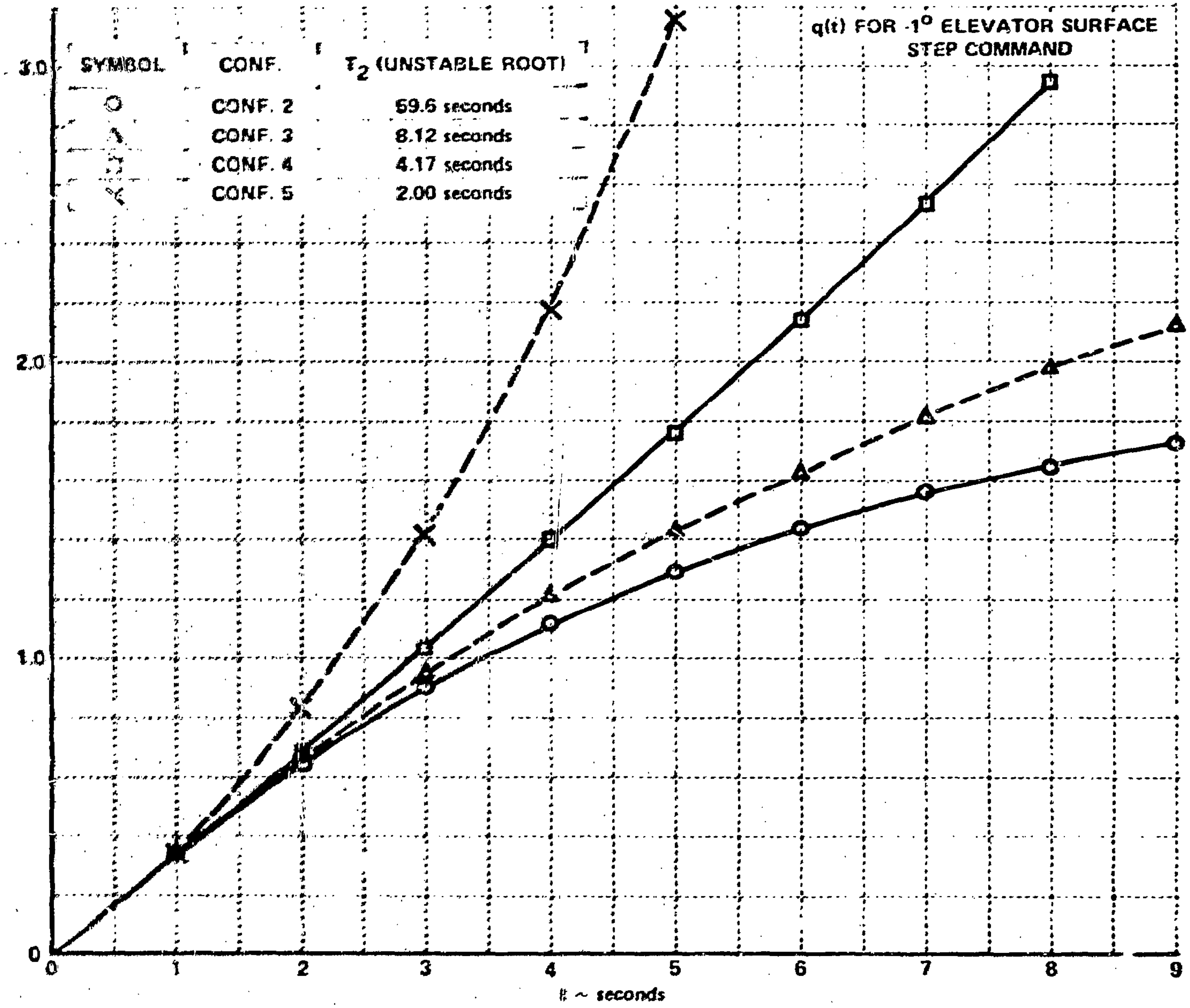


Figure II-1 EFFECT OF $C_{m_{\dot{\alpha}}}$ ON SHORT TERM PITCH RESPONSE

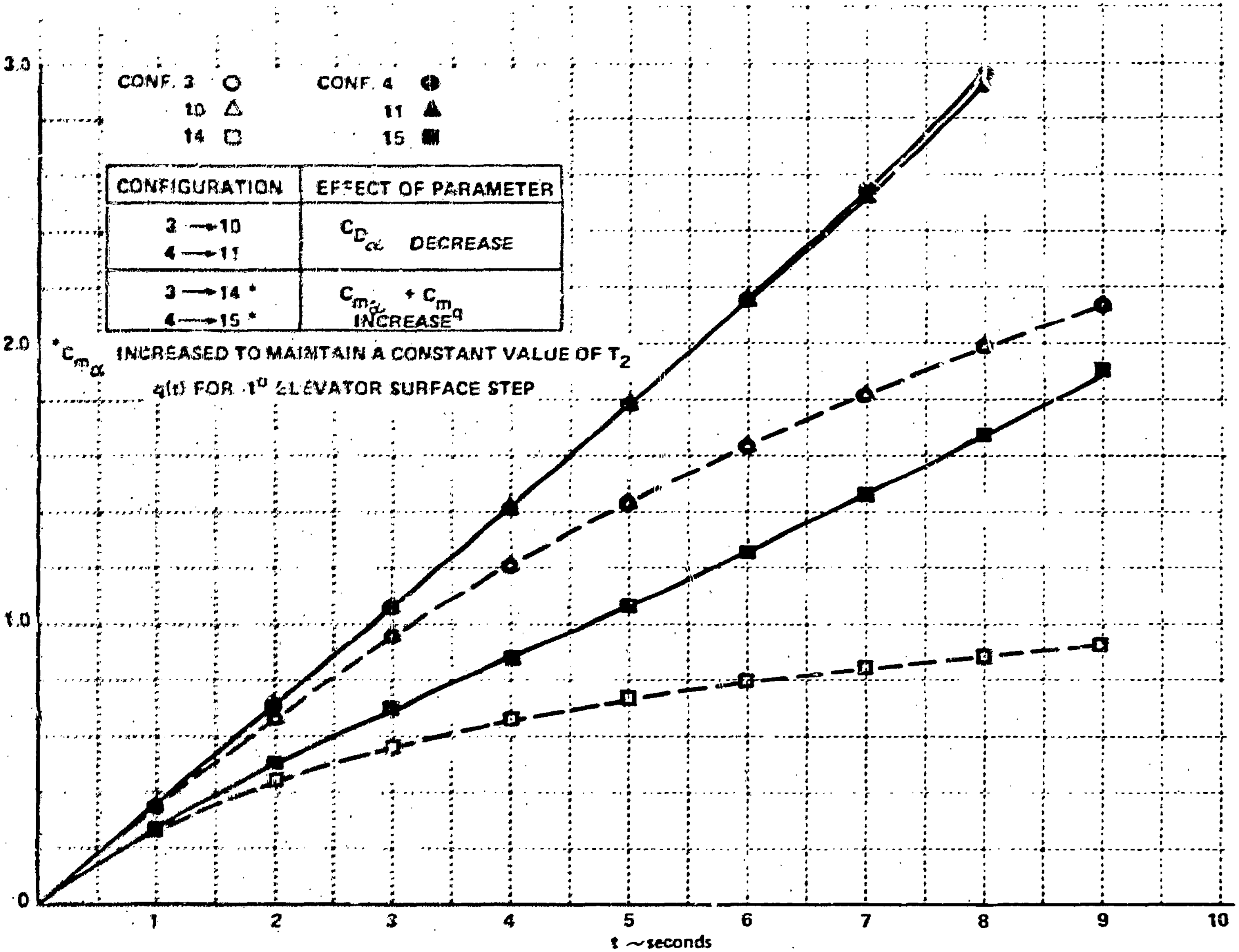


Figure II.2 EFFECT OF $C_{D_{\dot{\alpha}}}$ AND $(C_{m_{\dot{\alpha}}} + C_{m_q})$ ON SHORT TERM PITCH RESPONSE

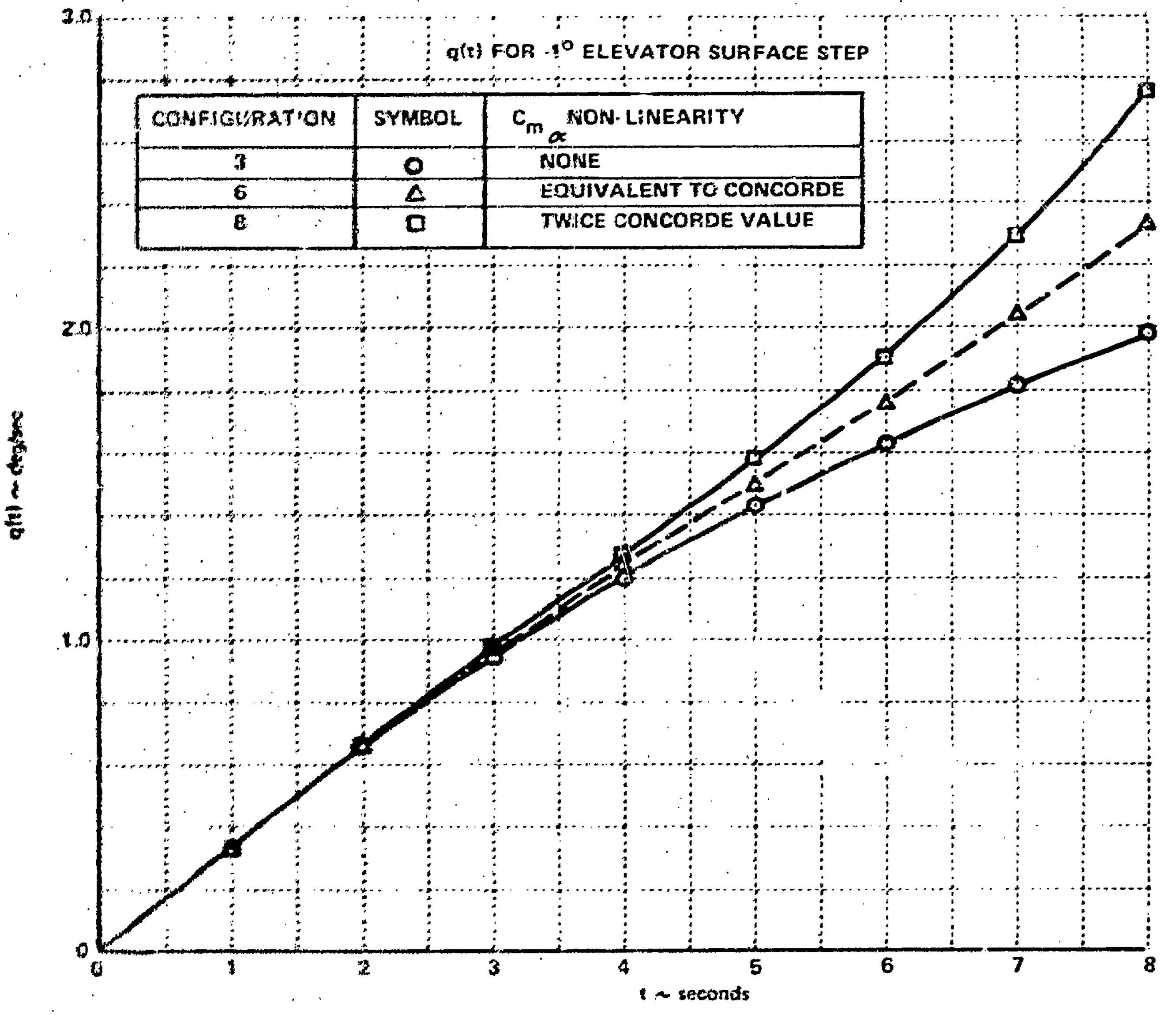


Figure II-3 EFFECT OF NON LINEAR C_{m_α} ON SHORT TERM PITCH RESPONSE

As previously stated, the time histories of pitch rate response to a negative elevator surface step appear to be of the form $A(1-e^{-\lambda t})$ for the first several seconds following the control input. In order to determine an "equivalent" first-order time constant the time history of $q(t_{n+1})-q(t_n)$ was plotted on semi-log paper. Examples of these plots are shown on Figures II-4 and II-5. The "equivalent" first-order time constant is defined by the best linear approximation to the slope measured on the attitude semi-log plots for ≤ 5 seconds. Table II-III documents the results for the statically unstable airplane configurations that were investigated in this program.

Table II-III also presents values obtained from two different but related approximations. These approximations will be discussed in the following paragraphs. The linearized three-degree-of-freedom longitudinal equations of motion were presented at the beginning of this appendix. The transfer function of attitude to an elevator input based on these equations can be written as follows (assuming $Z_{\dot{\alpha}} \ll 1, Z_q \ll 1$):

$$\frac{\theta}{\delta_e}(s) = \frac{N^{\theta}_{\delta_e}}{D^{\theta}_{\delta_e}} = \frac{\begin{aligned}(s+D_V)\Big[(M_{\delta_e}+Z_{\delta_e}M_{\dot{\alpha}})s+(Z_{\delta_e}M_{\alpha}-M_{\delta_e}Z_{\alpha})\\ -M_V(D_{\delta_e}s+D_{\alpha}Z_{\delta_e}-D_{\delta_e}Z_{\alpha})-Z_V(D_{\delta_e}M_{\dot{\alpha}}s+D_{\delta_e}M_{\alpha}-M_{\delta_e}D_{\alpha})\Big]\end{aligned}}{\begin{aligned}s(s+D_V)\Big[s^2-(M_q+Z_{\alpha}+M_{\dot{\alpha}})s+Z_{\alpha}M_q-M_{\alpha}+M_V(s\,D_{\theta}+D_{\alpha}-D_{\theta}Z_{\alpha})\\ +Z_V(D_{\alpha}s^2+s\left[D_{\theta}M_{\dot{\alpha}}-D_{\alpha}M_q\right]+D_{\theta}M_{\alpha})\Big]\end{aligned}} \qquad \text{(II.10)}$$

If the lower order terms (s^1, s^0) are neglected in the characteristic equation in order to determine a short term approximation, then the following equation results:

$$(D^{\theta}_{\delta_e})_{short\ term} = s^2\left[s^2+(-M_q-Z_{\alpha}-M_{\dot{\alpha}}+D_V)s+(Z_{\alpha}M_q-M_{\alpha})+D_V(-M_q-Z_{\alpha}-M_{\dot{\alpha}})+D_{\alpha}Z_V\right] \qquad \text{(II.11)}$$

The "equivalent" time constants presented in Table II-III for the characteristic equation approximation are determined from the lower frequency root of the bracketed quadratic factor in equation II.11.

If the effects of M_V and Z_V are neglected in equation II.10 then the following equation results:

$$\frac{\theta}{\delta_e}(s) = \frac{(M_{\delta_e}+Z_{\delta_e}M_{\dot{\alpha}})s+(Z_{\delta_e}-M_{\delta_e}Z_{\alpha})}{s\left[s^2-(M_q+Z_{\alpha}+M_{\dot{\alpha}})s+Z_{\alpha}M_q-M_{\alpha}\right]} \qquad \text{(II.12)}$$

This equation is identical to the result that would be obtained from a constant speed short-period approximation. The short-period approximation "equivalent" attitude time constant is determined from the lower frequency root of the above quadratic denominator expression. For the statically unstable configurations examined in this experiment, the quadratic expression in the

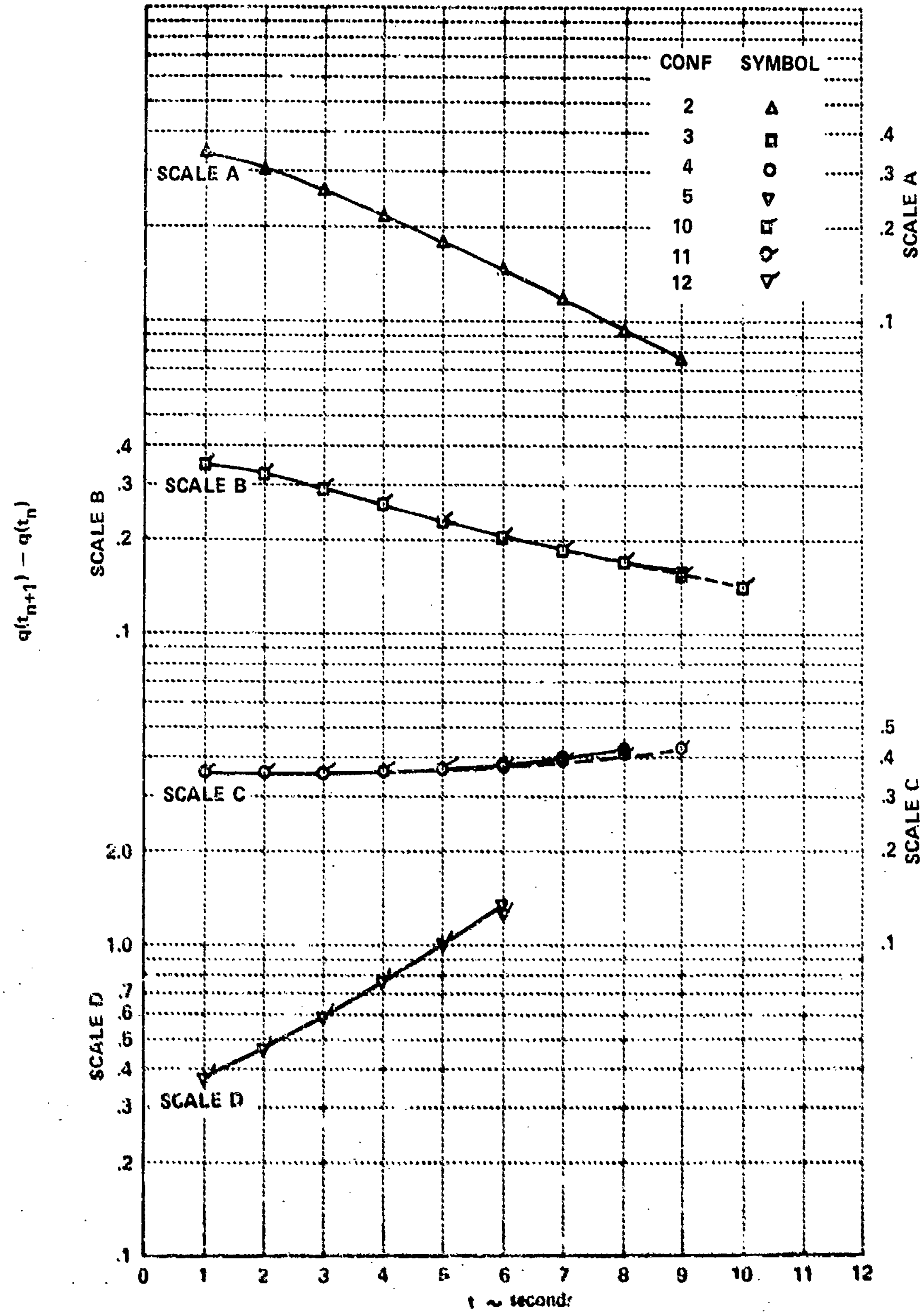


Figure II-4 EQUIVALENT ATTITUDE TIME CONSTANT (EFFECTS OF C_{m_α}, C_{D_α} VARIATION)

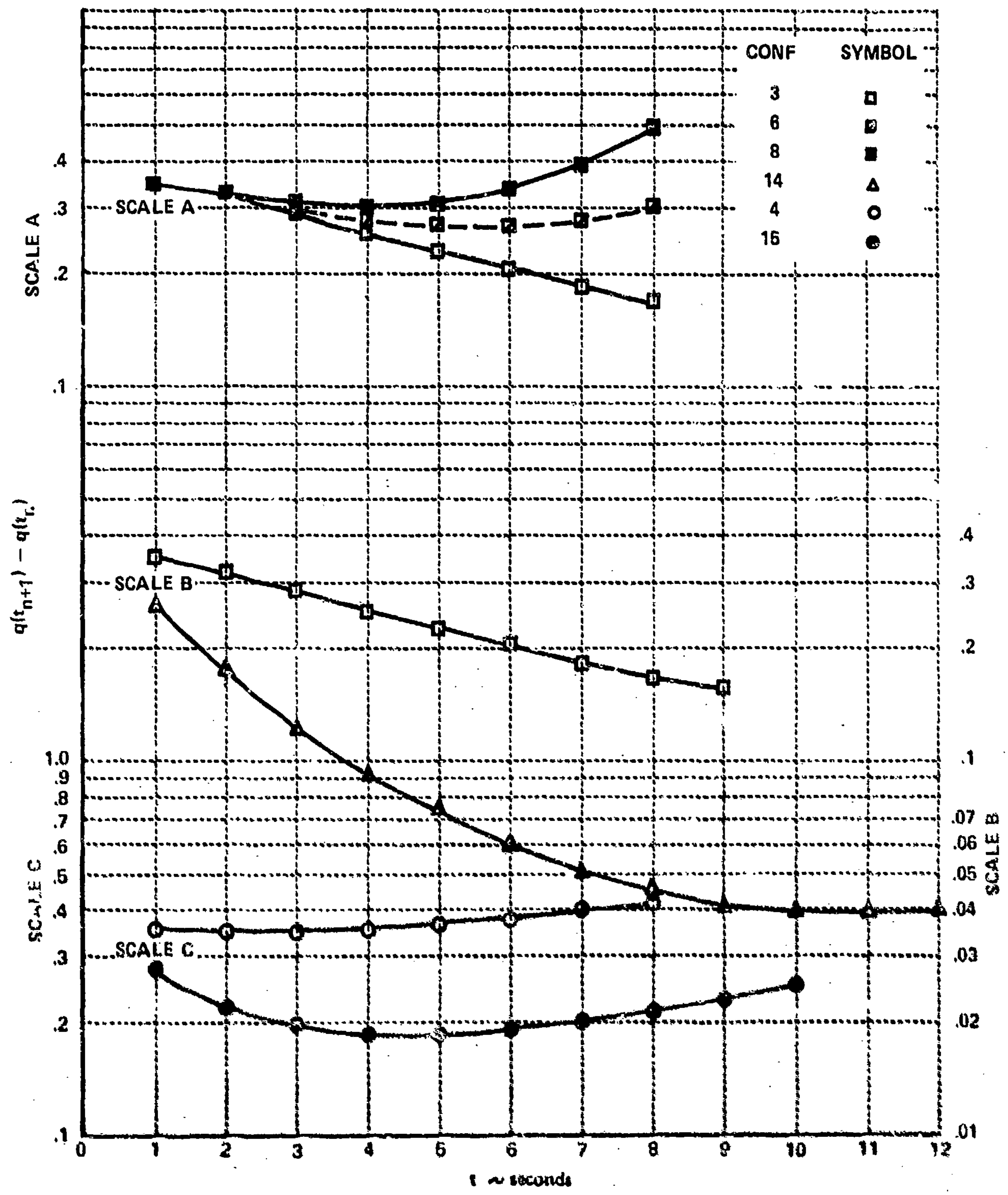


Figure II-5 EQUIVALENT ATTITUDE TIME CONSTANT (EFFECTS OF $(C_{m_{\dot{\alpha}}} + C_{m_q}), C_{m_\alpha}$ NONLINEARITY)

Table II-III

EQUIVALENT ATTITUDE TIME CONSTANTS

	Semilog plots		Characteristic Eq. Approximation		Short Period Approximation	
CONF.	$T_{1/2_\theta}$ ~ sec	T_{2_θ} ~ sec	$T_{1/2}$ ~ sec	T_2 ~ sec	$T_{1/2_{SP}}$ ~ sec	$T_{2_{SP}}$ ~ sec
2	3.60		3.57		3.65	
3	6.00		5.68		6.26	
4	∞		∞			37.31
5		2.60		2.9		2.60
6*	9.00		5.68		6.26	
7*		16.4	∞	109.0		37.31
8*	∞		5.68		6.26	
9*		6.1	∞	54.4		37.31
10	6.00		4.26		6.26	
11	∞		25.05			37.31
12		2.60		3.13		2.60
14	2.50		2.80		3.32	
15	14.80		9.45		19.94	
16		2.60		3.31		2.76
17*	2.20		2.80		3.32	
18*	∞		9.45		19.94	
19*		2.00		3.31		2.76

*Indicates configurations with nonlinear C_{m_α} .

denominator represents two real poles, one of which is essentially cancelled by the numerator zero. Thus the transfer function $\frac{\theta}{\delta_e}(s)$ essentially reduces to the form $\frac{A}{s(s+\lambda)}$ and, as previously indicated, the time response of attitude to an impulse would have the form $A(1-e^{-\lambda t})$. A comparison of the numbers presented in Table II-III indicates that a short period approximation can indeed be applied to the short term attitude response of an elevator control input, for the statically unstable airplane configurations evaluated in this research program. It is interesting to note that configurations which show a relatively small change in the time to double amplitude measured from angle of attack data show a much more significant change in the "equivalent" time constant of the attitude response (i.e., Configurations 4 and 5 from angle of attack data indicate a change in T_2 from 4.2 seconds to 2.0 seconds, however, these same configurations show a change from essentially neutral stability to a T_2 of 2.6 seconds in terms of the short term attitude response). This drastic change appears to be reflected in pilot comments and the pilot ratings for such configurations.

ELEVATOR TO TRIM IN STEADY BANKED TURNS

The previous paragraphs illustrated the fact that for the configurations evaluated in this program, the attitude response to elevator would be reasonably approximated for the short term by a short period approximation. The existence of a stable short period mode can be shown to be related to the control fixed maneuver margin (Reference 19), which is dependent on the slope of the elevator with incremental load factor determined from steady pull-up maneuvers or from steady banked turns. The equations of motion for a constant altitude steady banked turn are the following (Reference 20).

$$T\cos\epsilon - D = 0 \tag{II.13}$$

$$g\sin\mu - V\dot{\chi}\cos\mu = 0 \tag{II.14}$$

$$T\sin\epsilon + L - m(g\cos\mu + V\dot{\chi}\sin\mu) = 0 \tag{II.15}$$

Thus

$$\frac{g}{V}\tan\mu = \dot{\chi} \tag{II.16}$$

and $(T \sin \epsilon + L) \cos\mu = mg = W$

(II.17)

Thus $L + T \sin\epsilon = \frac{W}{\cos\mu} = nW$: in addition it can be shown that $q = \frac{g}{V}\tan\mu \sin\mu$ and substitution of $n = 1/\cos\mu$ then $q = \frac{g}{V}(n - 1/n)$. Since the turn is steady, the pitching moment equation must be solved for $\dot{q} = 0$. Using the notation previously introduced in the beginning of this appendix, the longitudinal equations of motion that result from a perturbation treatment are as follows:

$$M_\alpha \Delta\alpha + M_{\delta_e} \Delta\delta_e + \frac{z_T}{I_{yy}} \Delta T = M_q q \tag{II.18}$$

$$(D_\alpha + g)\Delta\alpha + D_{\delta_e}\Delta\delta_e - \frac{\cos(\alpha + i_T)_o}{m} \Delta T = 0 \tag{II.19}$$

$$Z_\alpha \Delta\alpha + Z_{\delta_e} \Delta\delta_e - \frac{\sin(\alpha_o + i_T)}{mV_o} \Delta T = \frac{-(n-1)g}{V_o} - Z_q q \tag{II.20}$$

where $q = \frac{g}{V_o}\left(n - \frac{1}{n}\right)$.

If the requirement for thrust change to hold increasing steady bank turns is ignored along with the drag equation, then the remaining equations can be solved for the change in elevator position with incremental g. The result is

$$\Delta\delta_e = \frac{(n-1)g}{V_o}\left[\frac{M_\alpha - \left(\frac{n+1}{n}\right)\left(M_q Z_\alpha - Z_q M_\alpha\right)}{M_{\delta_e} - Z_{\delta_e} M_\alpha}\right] \tag{II.21}$$

as $n \to \infty$, , the above equation reduces to $(Z_q << 1)$.

$$\frac{\Delta\delta_e}{n-1} = \frac{g}{V_o}\left[\frac{M_\alpha - M_q Z_\alpha}{M_{\delta_e} - Z_{\delta_e} M_\alpha}\right] \tag{II.22}$$

Thus as $(\Delta\delta_e/n\text{-}1) \rightarrow 0$, the square of the short period natural frequency $(M_q Z_\alpha - M_\alpha)$ must vanish.

If thrust is added to maintain constant altitude and constant velocity, then the relationship between incremental load factor and elevator required for trim becomes more complex. This case was examined using a six-degree-of-freedom nonlinear trim program rather than the perturbation analysis. The full perturbation analysis indicated relatively large changes in angle of attack would occur which would tend to invalidate using the linearized derivatives about the trim condition. Figures II-6 and II-7 present the results of this analysis for the statically unstable configurations evaluated in this program. A comparison of the slopes of these curves with the "equivalent" attitude response to elevator time constant indicates that there exists a reasonable correlation between the two quantities. Configurations 5, 12, 16 and 19, which were all rated essentially as uncontrollable (PR $\sim$ 10), all have a short time to double amplitude measured from angle of attack data ($T_2 \sim 2.0$ sec), and "equivalent" first order pitch time constant which is strongly unstable ($T_2 \sim 2.6$ sec), and for constant altitude turns have an unstable elevator to load factor gradient even at relatively small changes in load factor. For the configurations where C_{m_α} is not a function of angle of attack, for the relatively small load factor required to land an aircraft of the type investigated, Configurations 4 and 11 would appear to have zero control-fixed maneuver margin. The configurations with nonlinear C_{m_α} relationships would appear to be at the stick-fixed maneuver point for $\Delta n \leq .2$ g, however, this situation could be improved if the pilot increased the approach speed.

FLIGHT PATH STABILITY, SPEED STABILITY, AND "BACKSIDEDNESS"

During the landing approach flight phase, operation on the "backside" of the trim drag curve can result in coordination problems between throttle and elevator and increased pilot workload. When the elevator control is used to control attitude and altitude, then the airspeed response can be characterized by a first order mode which is directly related to the shape of the drag polar. For the experimental evaluations described in this report, the following equations relate flight path stability, speed stability, and "backsidedness."

Flight path stability as discussed in Reference 6 is described by the steady-state relationship between flight-path angle and velocity for an elevator input. Based on the equations of motion previously presented in this discussion, the following expression can be derived for $d\gamma/dV$ with constant throttle:

$$\frac{d\gamma}{dV} = \frac{M_{\delta_e}\left[Z_V(D_\alpha+g)-D_V Z_\alpha\right]+Z_{\delta_e}\left[M_\alpha D_V - M_V(D_\alpha+g)\right]+D_{\delta_e}\left[M_V Z_\alpha - Z_V M_\alpha\right]}{g\left[M_\delta Z_\alpha - Z_\delta M_\alpha\right]} \quad \text{(II.23)}$$

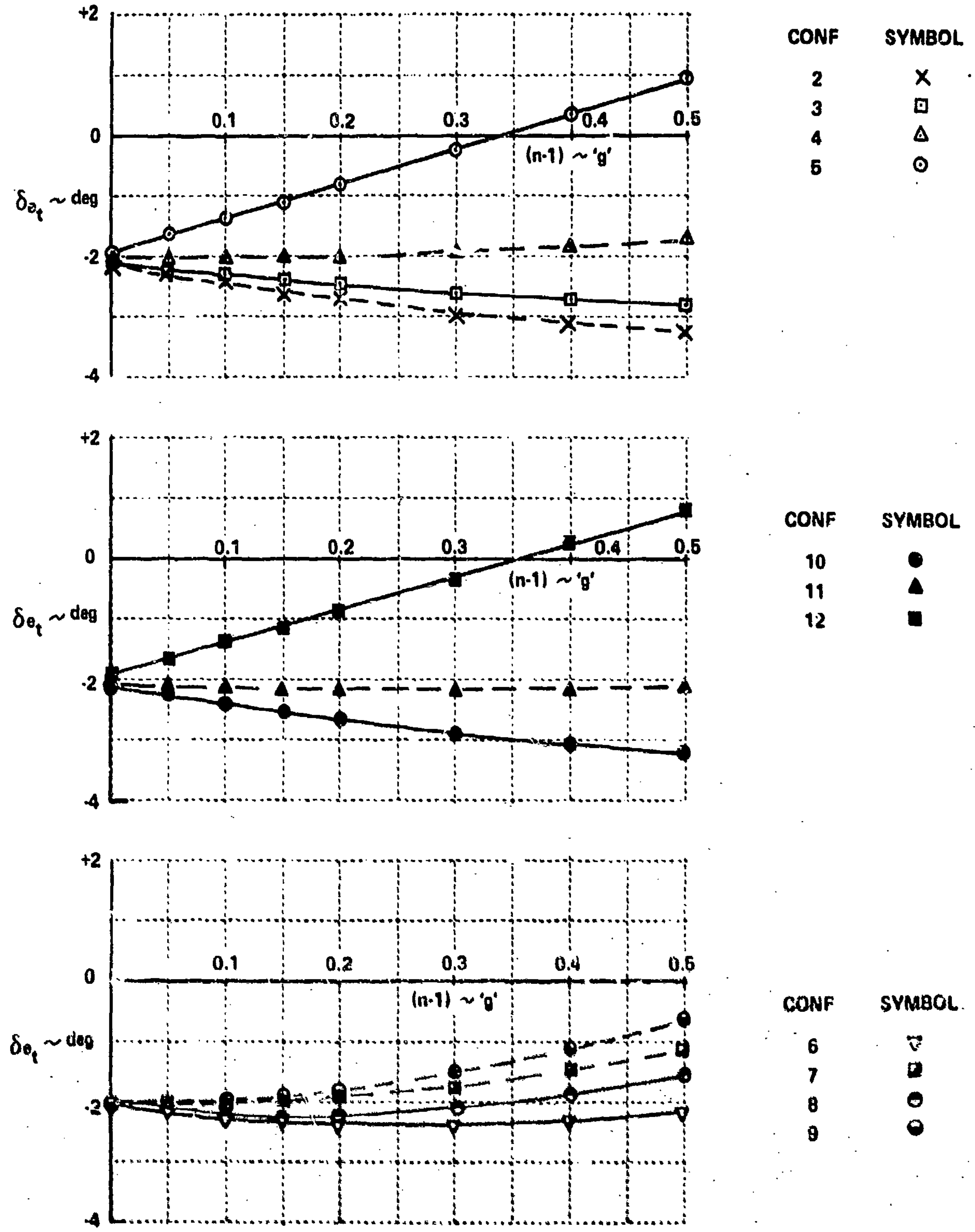
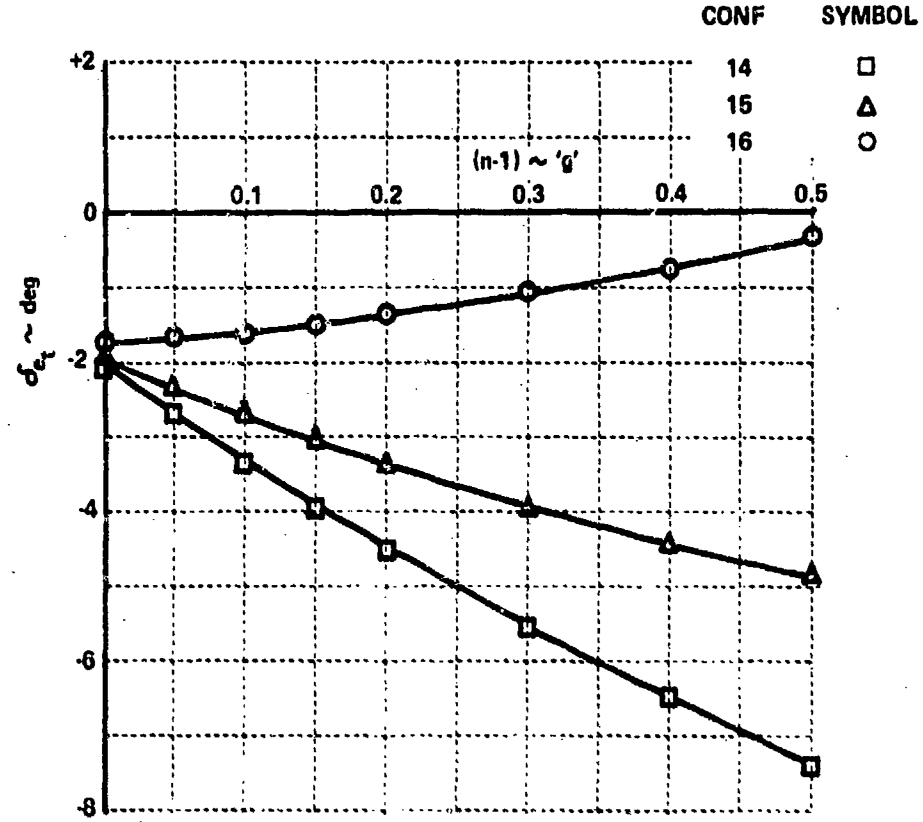


Figure II-6 ELEVATOR TO TRIM INCREMENTAL LOAD FACTOR (BASELINE $C_{m_{\dot{\alpha}}} + C_{m_q}$)



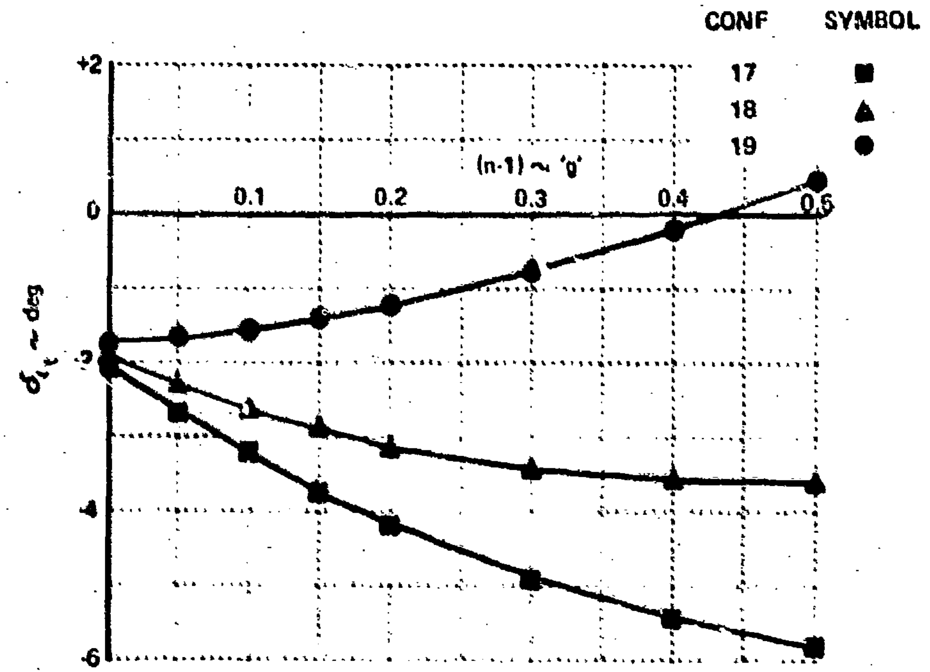


Figure II-7 ELEVATOR TO TRIM INCREMENTAL LOAD FACTOR (INCREASED $C_{m_{\dot{\alpha}}} + C_{m_q}$)

This expression may be rewritten as follows:

$$g\frac{d\gamma}{dV} = -D_V + Z_V\frac{\left[M_{\delta_e}(D_\alpha+g) - M_\alpha D_{\delta_e}\right]}{\left[M_{\delta_e}Z_\alpha - Z_{\delta_e}M_\alpha\right]} + M_V\frac{\left[D_{\delta_e}Z_\alpha - Z_{\delta_e}(D_\alpha+g)\right]}{\left[M_{\delta_e}Z_\alpha - Z_{\delta_e}M_\alpha\right]} \tag{11.24}$$

If M_V is neglected and it is assumed that $\left|\dfrac{M_\alpha D_{\delta_e}}{M_{\delta_e}(D_\alpha+g)}\right| << 1$ and $\left|\dfrac{Z_{\delta_e}M_\alpha}{M_{\delta_e}Z_\alpha}\right| << 1$, then the previous expression becomes

$$g\frac{d\gamma}{dV} = -D_V + \frac{Z_V(D_\alpha+g)}{Z_\alpha} \tag{11.25}$$

This form of the equation for flight path stability is directly related to the speed stability first order mode. The formulation for the speed stability mode is obtained by assuming that the pitching moment equation can be kinematically constrained such that this equation is identically satisfied and, in addition, $\gamma_o = 0$ and $\Delta\gamma = 0$, thus $\Delta\theta = \Delta\alpha$. Using these conditions in the remaining equations of motion yields (neglecting controls):

Drag

$$\Delta\dot{V} + D_V\Delta V + (D_\alpha+g)\,\Delta\alpha = 0 \tag{11.26}$$

Lift

$$Z_V\Delta V + Z_\alpha\Delta\alpha = 0 \tag{11.27}$$

Solving these two equations simultaneously yields for velocity the following equation

$$\Delta\dot{V} + \left(D_V - \frac{(D_\alpha+g)Z_V}{Z_\alpha}\right)\Delta V = 0 \tag{11.28}$$

where the speed stability root is defined by

$$\lambda_{\text{speed stability}} = D_V - \frac{(D_\alpha+g)Z_V}{Z_\alpha}$$

which is equal and opposite to $g \frac{d\gamma}{dV}$ under certain constraints. Reference 16 also illustrates that these parameters are directly related to the slope of the trim drag and thrust curve as a function of velocity. Thus

$$g \frac{d\gamma}{dV} \doteq \frac{d(T_t/W)}{dV} \tag{11.29}$$

Table II-IV indicates the values obtained for the different measures of "backsidedness" for the configuration examined in this experiment at altitude (out of ground effect) and when the center of gravity is 16 feet above the runway. The results are presented in terms of degrees/knot comparison with the requirements of Reference 6. The experimental design varied the "backsidedness" at altitude by modification of the drag polar, such that all configurations out of ground effect essentially achieved the same trim condition at the reference velocity of 160 knots IAS. The induced drag was reduced for Configurations 10, 11, 12 and 20. The primary purpose was to examine the effect of "backsidedness" on pilot opinion and workload for the statically unstable configurations examined in this program. It should be noted that placing the airplane in the "bucket" of the power required curve $\left(\frac{d(T/W)}{dV} = 0\right)_{V = V_{ref}}$ by reducing drag (C_{D_α}) will also slightly reduce the aperiodic unstable mode in the airplane linearized three-degree-of-freedom longitudinal characteristic equation. As previously shown, the reduction of (C_{D_α}) used in this program will have no significant effect on the short term response of attitude to an abrupt elevator control input. The reduction of "backsidedness" with altitude is primarily due to the decrease in induced drag and the increase in the lift slope curve as the aircraft enters ground effect.

Table II-IV

FLIGHT PATH STABILITY ~ DEGREES/KNOT

	h = 400 feet			h = 16 feet		
CONF	A	B	C	A	B	C
1	.1045	.1292	.1270	.0648	.1118	.1150
2	.1043	.1043	.1070	.0633	.0774	.077
3	.1043	.1024	.0980	.0636	.0745	.066
4	.1043	.0984	.0950	.0641	.0683	.066
5	.1044	.0882	.0920	.0653	.0540	.052
6	.1043	.1238	.092	.0637	.0773	.074
7	.1043	.0981	.1014	.0648	.0709	.070
8	.1033	.1010	.1014	.0647	.0803	.075
9	.1043	.0979	.0890	.0643	.0737	.076
10	-.0035	-.0033	0.0	-.0309	-.0282	0.0
11	-.0034	-.0030	0.0	-.0306	-.0296	0.0
12	-.0034	-.0022	0.0	-.0300	-.0326	-.034
13	.1045	.1292	.1543	.0648	.1118	.101
14	.1043	.0988	.100	.0640	.0690	.063
15	.1044	.0908	.096	.0650	.0575	.056
16	.1045	.0768	.076	.0665	.0399	.048
17	.1043	.0985	.098	.0642	.0746	.072
18	.1044	.0905	.089	.0653	.0622	.065
19	.1045	.0766	.080	.0667	.0434	.044
20	-.0034	-.0055	0.0	-.0302	-.0194	-.025

Reference requirements:

Level 1 - $\frac{d\gamma}{dV} \leq 0.06$ degrees/knot

Level 2 - $\frac{d\gamma}{dV} \leq 0.15$ degrees/knot

Level 3 - $\frac{d\gamma}{dV} \leq 0.24$ degrees/knot

where:

A refers to the parameter as determined from 'speed stability' (Eq. II.28))

B refers to the parameter as determined from $(d\gamma/dV)$ steady state (Eq. II.23)

C refers to the parameter as determined from the trim thrust slope (Eq. II.29)

APPENDIX III

TYPICAL MODEL-FOLLOWING IN-FLIGHT RESPONSES AND FEEDFORWARD AND FEEDBACK GAINS

The degree of longitudinal model-following to a manual elevator doublet is shown in Figure III-1 and to an automatic classical throttle step input in Figure III-2. The degree of lateral-directional model following to a classical aileron step and rudder step can be seen on Figure III-3 and Figure III-4, respectively. The model following achieved after a rudder doublet has been made is shown in Figure III-5. The longitudinal and lateral-directional model following accomplished on a typical approach can be seen from a comparison of the in-flight records on Figure III-6.

The longitudinal feedforward gains used in this research program are presented in Table III-I. The longitudinal feedback gains are shown in Table III-II. For the lateral-directional, the feedforward gains are presented in Table III-III and the feedback gains in Table III-IV.

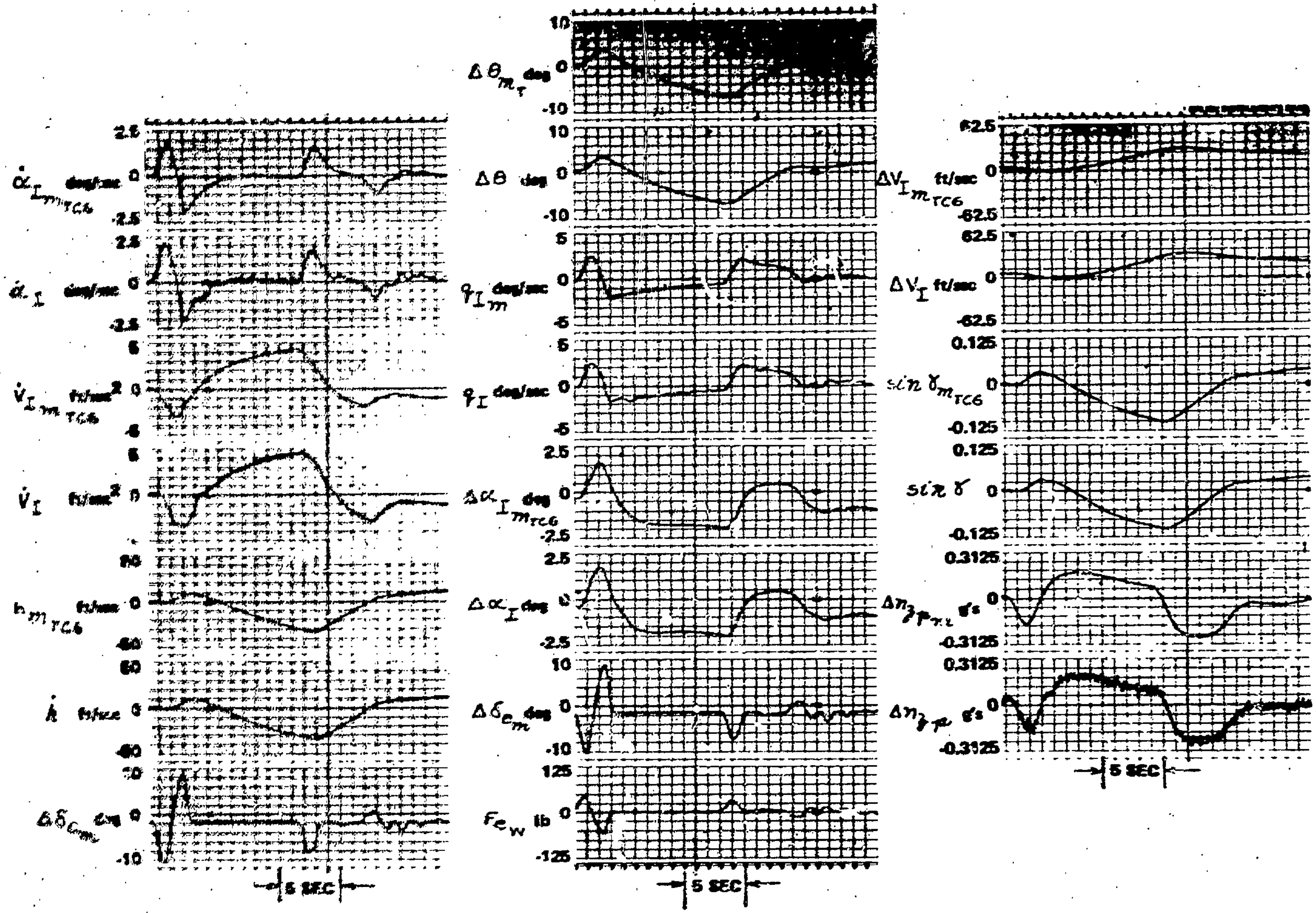


Figure III-1 MODEL FOLLOWING RESPONSES TO MANUAL ELEVATOR DOUBLET, CONFIGURATION 6, FLIGHT 182

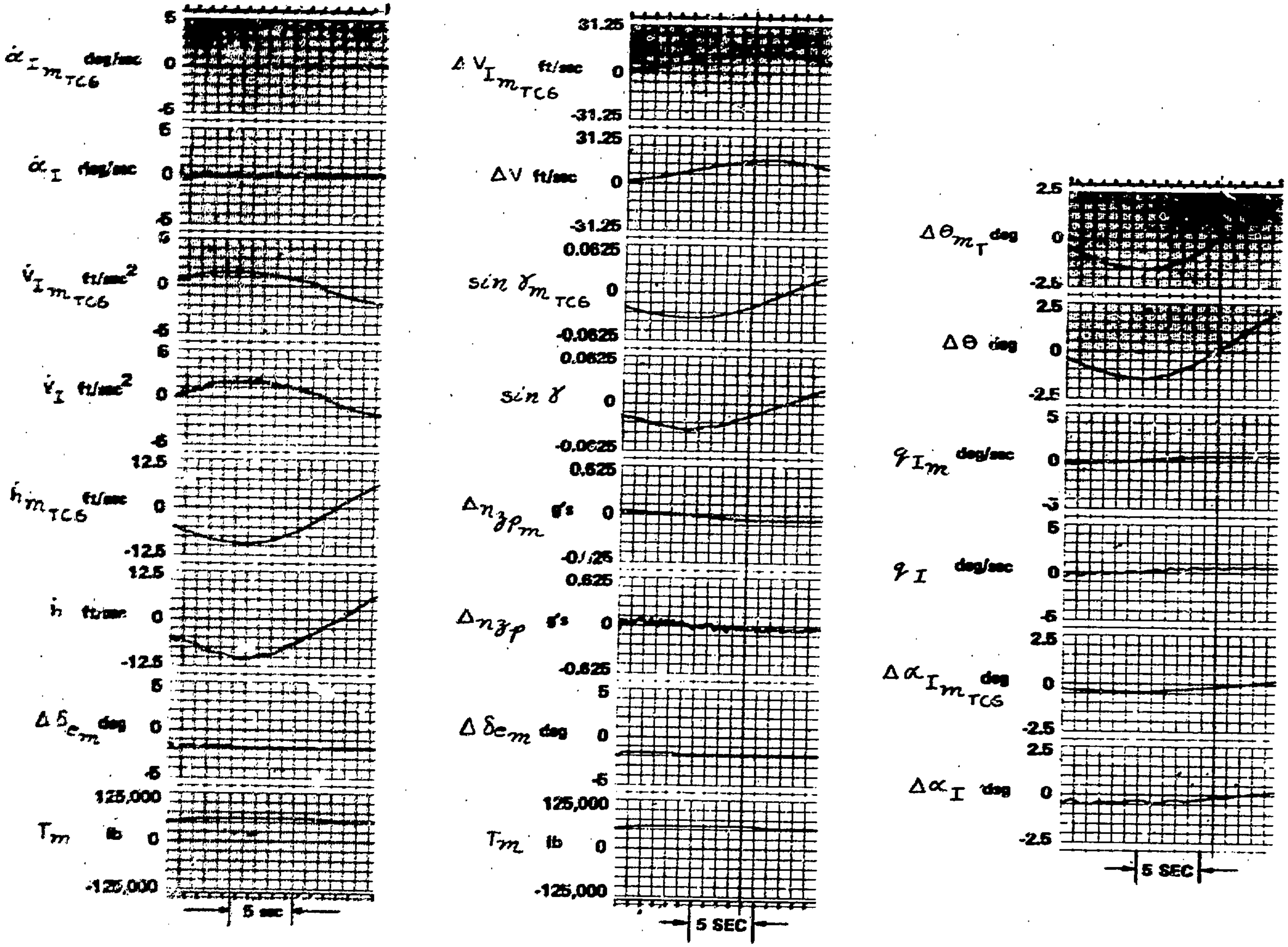


Figure III-2 MODEL FOLLOWING RESPONSES TO AN AUTOMATIC THROTTLE STEP INPUT, CONFIGURATION 6, FLIGHT 182

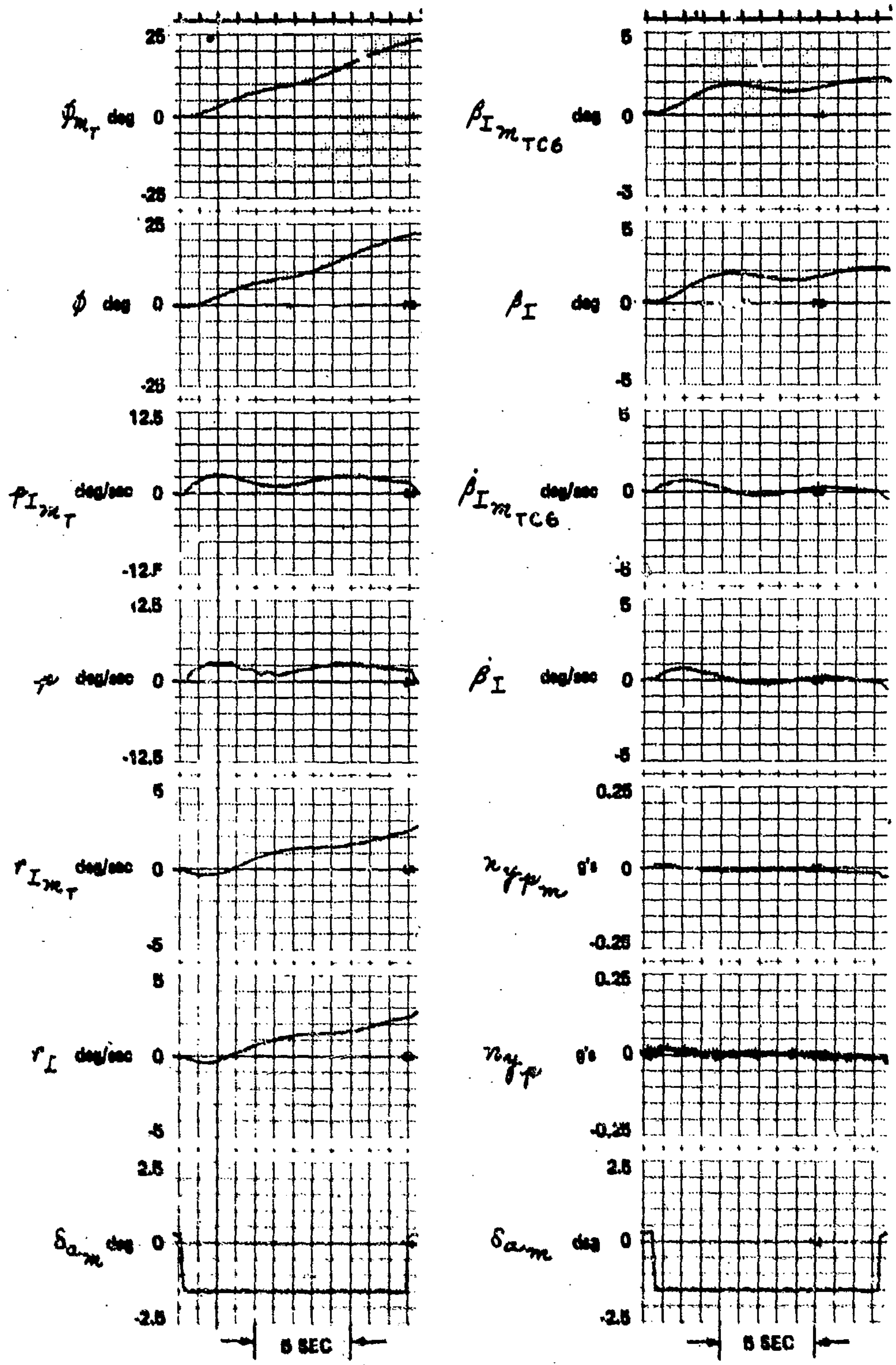


Figure III-3 MODEL FOLLOWING RESPONSES TO AN AUTOMATIC AILERON STEP INPUT, CONFIGURATION 6, FLIGHT 182

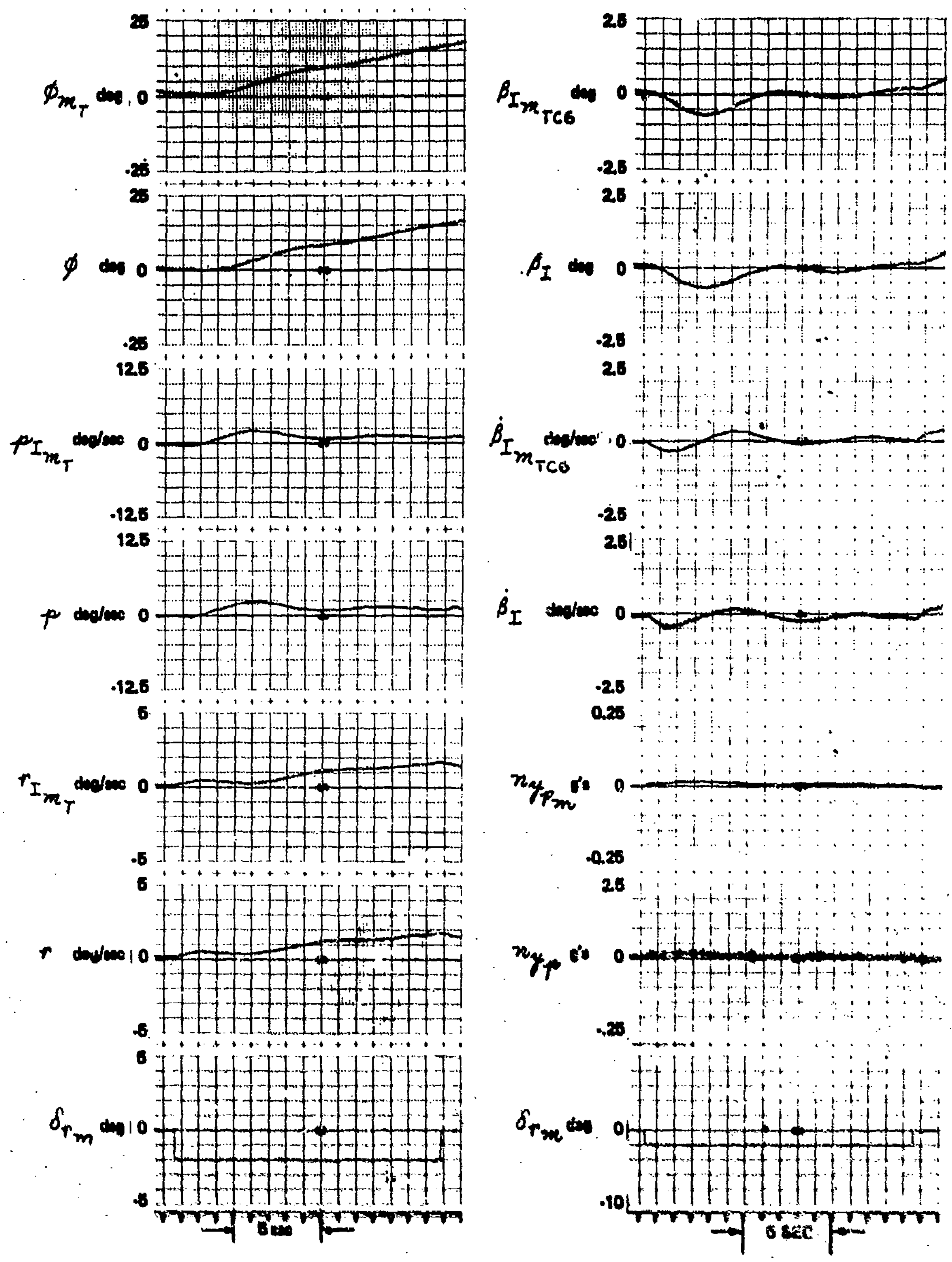


Figure III-4 MODEL FOLLOWING RESPONSES TO AN AUTOMATIC RUDDER STEP INPUT, CONFIGURATION 6, FLIGHT 182.

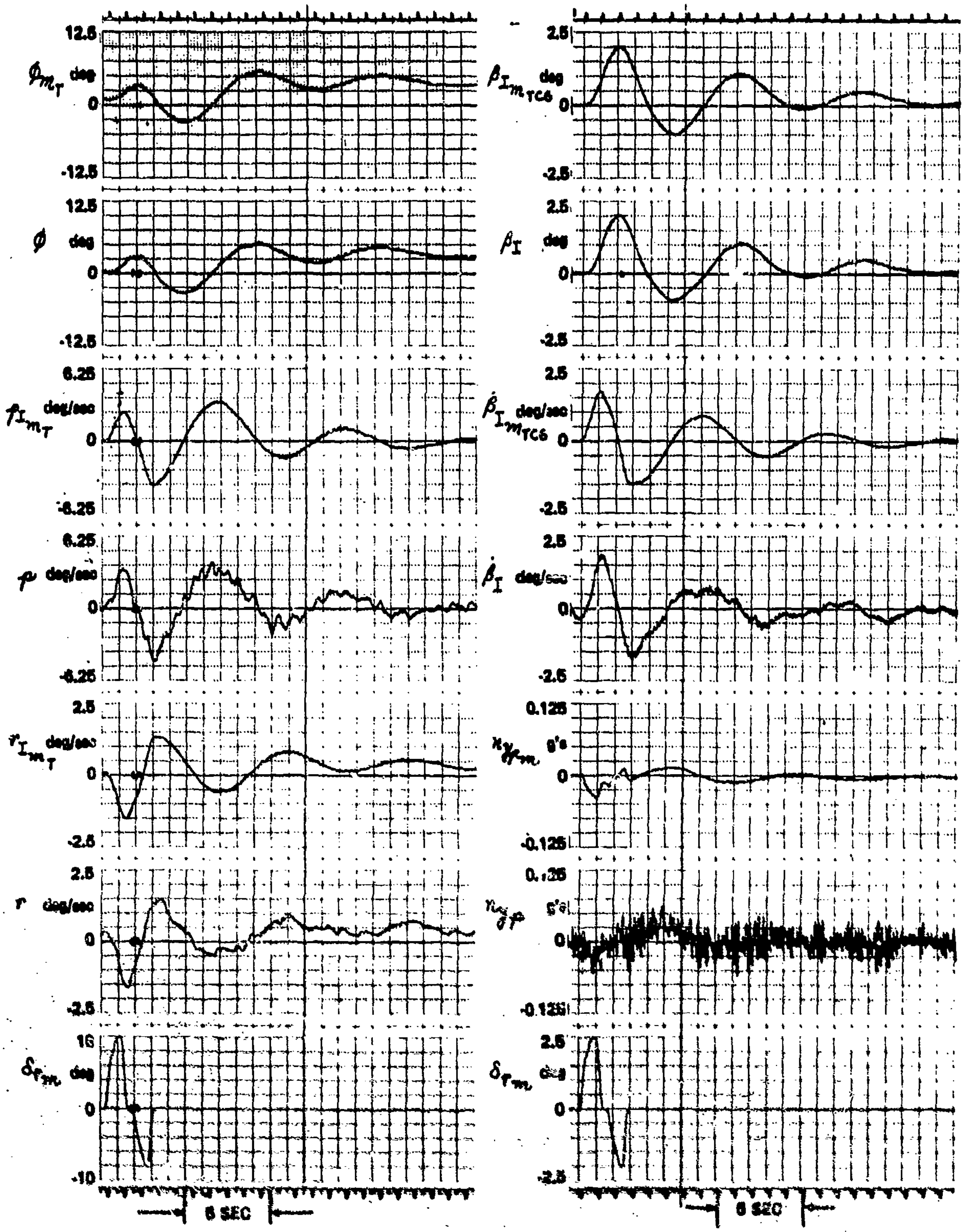


Figure III-5 MODEL FOLLOWING RESPONSES TO A MANUAL RUDDER DOUBLET INPUT, CONFIGURATION 6, FLIGHT 182

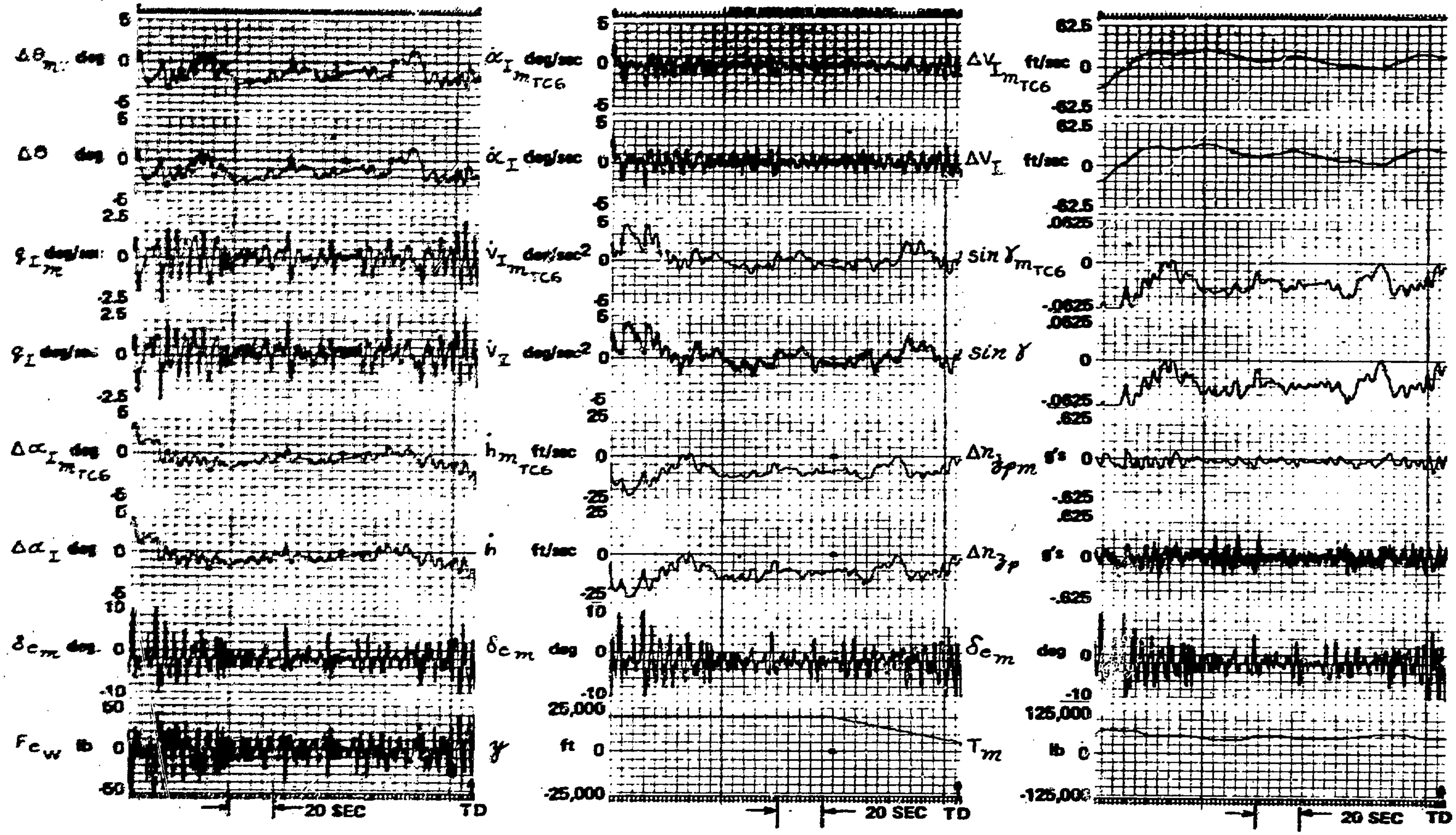


Figure III-6 MODEL FOLLOWING DURING IFR APPROACH AND VFR LANDING (ALTITUDE ~2000 ft TO TOUCHDOWN, FLIGHT 182, CONFIGURATION 6, PILOT B)

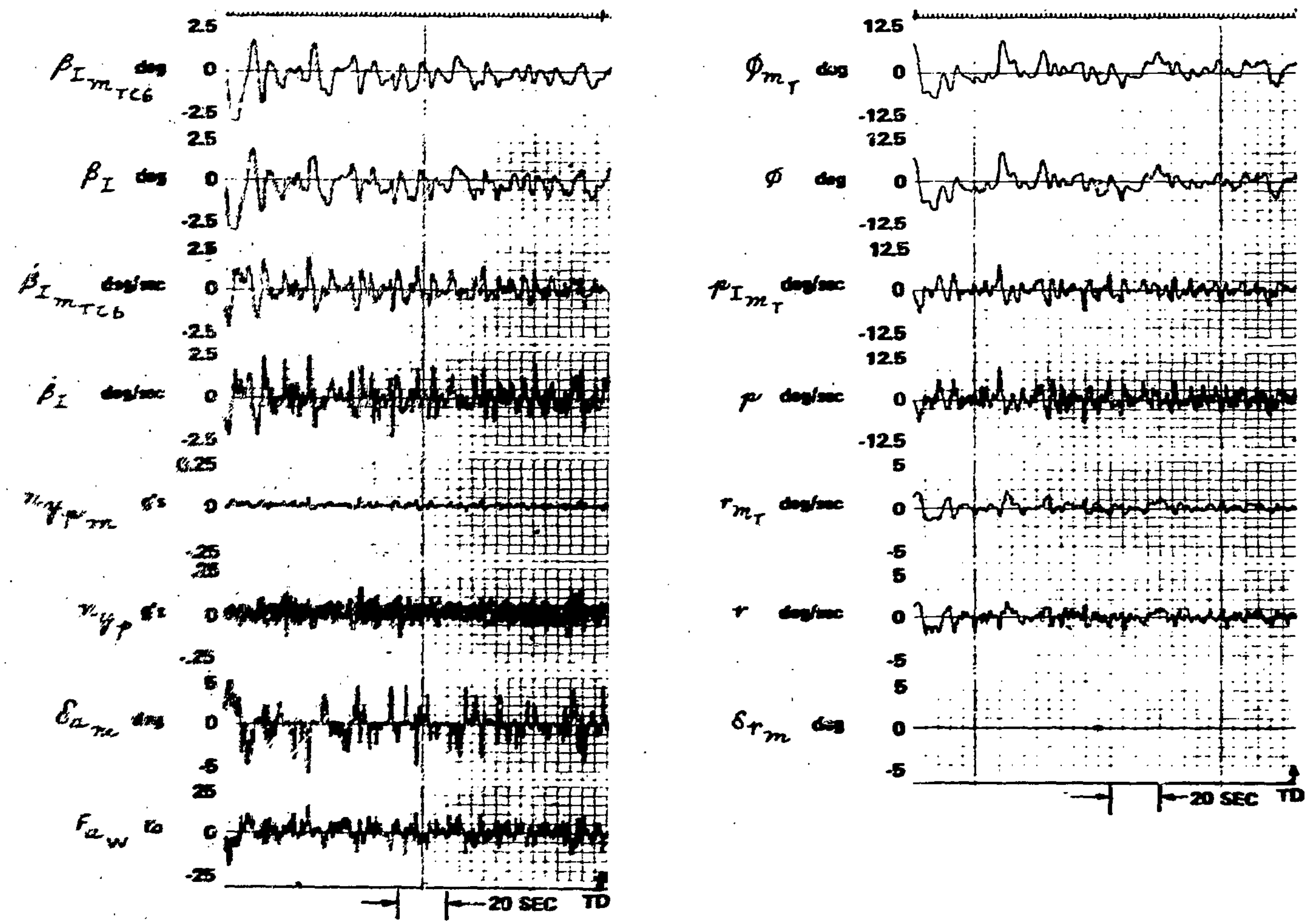


Figure III-6 (cont.) MODEL FOLLOWING DURING IFR APPROACH AND VFR LANDING (ALTITUDE ~ 2000 ft TO TOUCHDOWN, FLIGHT 182, CONFIGURATION E, PILOT B)

Table III-I

LONGITUDINAL FEEDFORWARD GAINS

GAINS	VALUE
$(\delta_e/\dot{q}_m)$	-0.313
(δ_e/q_m)	-0.171
$(\delta_e/\Delta V_{m_{TCG}})$	+0.021
$(\delta_e/\dot{\alpha}_{m_{TCG}})$	-0.109
$(\delta_e/\Delta\alpha_{m_{TCG}})$	0.204
$(\delta_e/\Delta n_{z_{m_{TCG}}})$	2.8
$(\delta_x/\dot{V}_{m_{TCG}})$	7.69
$(\delta_x/\Delta V_{m_{TCG}})$	-0.024
$(\delta_x/\Delta\alpha_{m_{TCG}})$	-1.43
$(\delta_x/\Delta \sin\gamma)$	247.0
$(\delta_x/\Delta n_{z_{m_{TCG}}})$	-28.6
$(\delta_z/\Delta V_{m_{TCG}})$	-0.318
$(\delta_z/\Delta\alpha_{m_{TCG}})$	-7.0
$(\delta_z/\Delta n_{z_{m_{TCG}}})$	-43.0

Table III-II

LONGITUDINAL FEEDBACK GAINS

GAINS	VALUE
(δ_e/e_q)	-0.875
(δ_e/e_θ)	-5.54
$(\delta_e/\int e_\theta)$	-4.88
$(\delta_x/e_{\dot{V}})$	1.23
$(\delta_x/e_{\Delta V})$	2.50
(δ_x/e_γ)	6.97
$(\delta_z/e_{\dot{\alpha}})$	-1.60
$(\delta_z/e_{\Delta\alpha})$	-8.0
$(\delta_z/\int e_{\Delta\alpha})$	-8.0

Table III-III

LATERAL-DIRECTIONAL FEEDFORWARD GAINS

GAIN	VALUE
$(\delta_a / \dot{p}_m)$	-0.950
(δ_a / p_m)	-1.60
$(\delta_a / \dot{\beta}_{m_{TCG}})$	0.20
$(\delta_a / \beta_{m_{TCG}})$	-1.35
$(\delta_a / \dot{r}_{m_T})$	-0.744
(δ_a / r_{m_T})	0.908
(δ_r / p_m)	-0.22
(δ_r / ϕ_m)	-0.143
$(\delta_r / \dot{r}_m)$	-0.848
(δ_r / r_m)	0.948
$(\delta_r / \dot{\beta}_{m_{TCG}})$	1.24
$(\delta_r / \beta_{m_{TCG}})$	0.964
$(\delta_y / \dot{r}_m)$	0.424
$(\delta_y / \beta_{m_{TCG}})$	2.43
$(\delta_y / n_{y_{m_{TCG}}})$	88.4

Table III-IV

LATERAL-DIRECTIONAL FEEDBACK GAINS

GAIN	VALUE
(δ_a/e_p)	-3.52
(δ_a/e_ϕ)	-3.52
(δ_r/e_r)	-2.0
$(\delta_r/e_{\beta_{TCG}})$	1.69
$(\delta_r/\int e_{\beta_{TCG}})$	2.20
$(\delta_y/e_{\beta_{TCG}})$	10.0

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